CRANFIELD UNIVERSITY

YUN ZHAI

EARLY COST ESTIMATION FOR ADDITIVE MANUFACTURE

SCHOOL OF ENGINEERING
MSc By Research

MSc
Academic Year: 2011 - 2012

Supervisor: Dr. Helen Lockett
September 2012

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ABSTRACT

Additive Manufacture (AM) is a novel manufacturing method; it is a process of forming components by adding materials. Owing to material saving and manufacturing cost saving, more and more research has been focused on metal AM technologies. WAAM is one AM technology, using arc as the heat sources and wire as the material to create parts with weld beads on a layer-by-layer basis. The process can produce components in a wide range of materials, including aluminum, titanium and steel. High deposition rate, material saving and elimination of tooling cost are critical characteristics of the process.

Cost estimation is important for all companies. The estimated results can be used as a datum to create a quote for customers or evaluate a quote from suppliers, an important consideration for the application of WAAM is its cost effectiveness compared with traditional manufacture methods. The aim of this research is to find a way to develop a cost estimating method capable of providing manufacturing cost comparison of WAAM with CNC. A cost estimation model for CNC machining has been developed. A process planning approach for WAAM was also defined as part of this research. An Excel calculation spreadsheet was also built and it can be easily used to estimate and compare manufacture cost of WAAM with CNC.

Using the method developed in this research, the cost driver analysis of WAAM has been made. The result shows that reduced material cost is the biggest cost driver in WAAM. The cost comparison of WAAM and CNC also has been made and the results show that with the increase of buy-to-fly ratio WAAM is more economical than CNC machining.

Keywords:

ADDITIVE MANUFACTURE, COST ESTIMATION, PROCESS PLANNING, CNC MACHINING

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LIST OF ABBREVIATIONS

AM	Additive Manufacture
CNC	Computer Number Control
CAD	Computer Aided Design
CAPP	Computer Aided Process Planning
COMAC	Commercial Aircraft Corporation of China, Ltd.
DDM	Direct Digital Manufacturing
DMLS	Direct Metal Laser Sintering
EBM	Electric Beam Welding
FDM	Fused Deposition Modeling
GDP	Group Design Program
HLM	Hybrid Layer Manufacturing
LENS	Laser-engineer Net Shaping
LOM	Laminated Object Manufacturing
PP	Plaster-based 3D Printing
RM	Rapid Manufacture
RP	Rapid Prototyping
RT	Rapid Tooling
SAW	submerge arc welding
SFF	Solid Freedom Fabrication
SLS	Selective Laser Sintering
SLA	Stereolithography
TS	Travel Speed
WFS	Wire Feed Speed
WELPC	Welding engineering & Laser Processing Centre
WAAM	Wire and Arc Additive Manufacture

Nomenclature

C_m = Material cost

$C_{c\text{-}m}$ = Cost of Material

C_s = set-up cost

C_t = Cost of providing a new cutting edge

C_{fm} = Finish-machining cost

C_{rm} = Rough-machining cost

C_n = Non-productive cost

C_g = Shielding gas cost

C_w = welding cost

C_{dm} = Deposition material cost

C_{wire} = Filler wire metal cost

C_{sm} = Substrate material cost

C_{sub} = Substrate sheet metal cost

C_{gc} = Gas cost per cylinder

C_C = Wire change cost

$C_{m\text{-}t}$ = Machining and tool replacement cost

C_{waam} = WAAM cost

D_w = Diameter of filler wire

E_p = Part built efficiency

E_t = Build time efficiency

M_w = Mass of filler wire per roll

n = Taylor tool-life index

N_s = Number of finish-machining operations

N_d = Number of deposition operations

N_{op} = Number of operations

Q = Proportion of t_m for which a point on the tool cutting edge is contacting

R_m = Machine hourly rate

R_o = Operator hourly Rate

R_u = Machine utilization Rate

R_g = Gas flow Rate

t_m= Machining time(time the machining tool is operating)

t = Tool life while the cutting edge is contacting the workpiece

t_{tc}= Tool-changing time

t_{mc} = Machining time when the optimum cutting speed is used,

t_{mp} = Machining time when the limited power speed is used

t_s = Set-up time

t_c = Wire change time

t_{sd} = Deposition machine setup time

t_{sf} = Finish-machining machine setup time

t_{nf} = Finish-machining non-productive time

t_n = Non-productive time

t_u = Machine utility time

t_w = time of welding

V_{dm} = Volume of deposition

V_b = Volume of billet

V_{sm} = Volume of substrate

V_{gc} = Volume of cylinder

$\boldsymbol{\rho}_m$ = Density of material

$\boldsymbol{\rho}_{wire}$ = Density of filler wire

$\boldsymbol{\rho}_{sub}$ = Density of substrate

1 Introduction

1.1 Background

Additive Manufacture defines a series of technologies. All AM technologies can build physical objects from computer aided design (CAD) files by adding forming material and the component seems to “grow” from nothing to completion. The definition is opposite to subtractive manufacture methodologies[1].

Over past decades, the development and application of AM has been significantly increasing. AM manufactures components in a wide scope of materials from non-metals to metals. Compared with traditional manufacture technologiese[1], AM has some remarkable advantages are as follow [1; 2]:

- Reduce material waste (compared with traditional method).
- Can build near net-shape part with highly complex geometries directly from 3D CAD data without tooling.
- Parts show good mechanical properties (compared with casting).
- Reduce leading time in manufacturing process.

But the disadvantages of AM are as follow[1; 2]:

- Manufacture speed is slow compared with traditional methods at present.
- The manufacture process is difficult control.
- The process is without tooling, but the substrate is necessary.
- The surface quality is not very excellent and requires a finishing process.

In 1925, wire and arc based additive manufacture was used to fabricate decorative items. In the later 1970s, in West Germany, a wire based process was used to submerge arc welding (SAW) for the fabrication of large metallic components. This technology emerged much earlier than stereolithography[1] in the 1980’s. Owing to the material saving and weight reduction and excellent mechanical properties, researches began to focus on metal[2].

In the next 20 years, it is predicted that air passenger miles will grow at more than 5% per year, which means that 24,300 new passenger and freight aircrafts will be needed and the values of sales will be expected to be $2.8 trillion 2026.

However, the buy-to-fly ratio for conventional manufacturing is about 10:1, so 20 million tone of billet materials are required to build these aircraft and 90% materials would be machined away[3].

By 2016, AM products and services will reach $3.1 billion worldwide, predicted by Wohlers Associates. By 2020, the industry is expected to hit $5.2 billion[4].

At Boeing and Airbus special AM research teams were built to find the best way to use AM in aircraft manufacture. Same research works have been carried out by many universities. A research program named Wire and Arc Additive Manufacturing (WAAM) has been done at Cranfield University [5]. WAAM is one of AM technologies, the process using Arc as heat resource and wire as material to create AM parts. The aim of WAAM is to manufacture large and high quality parts at very high deposition rate[5]. In a WAAM manufacture process, 3D metallic parts are built by depositing beads of weld metal on a layer-by-layer basis. Finishing process (milling or grinding) is arranged after deposition to meet surface and dimension requirements of end use parts[6]. The manufacture equipment of WAAM is the welding machine and the finish-machining machine. This research is focus on WAAM technologies which developed in Cranfield University.

Compared with traditional manufacture, one of the most important advantages of WAAM is its low cost in terms of material reduction, leading time reduction and tooling reduction[5; 6]. With the development of WAAM technology more and more companies choose WAAM to manufacture parts, therefore, a method is needed to estimate manufacture cost of WAAM and to compare manufacture cost of WAAM with that of traditional manufacture methods. In the meantime, there are other advantages of cost estimation. Firstly, the results of cost estimation will provide designers with information about the cost of WAAM parts, who can seek alternative designs to get more reasonable cost before actual manufacture. Secondly, the results of cost estimation can be used to investigate cost drivers in WAAM manufacture process and help planners choose accurate manufacture parameters and make a more reasonable process planning.

Thirdly, when selecting machining methods, cost estimation results can provide managers with useful information.

1.2 Aims and Objectives

The aim of this research is to investigate the cost drivers of WAAM and compare the cost of WAAM and that of CNC machining. For this purpose, the objectives of the research works are shown as below:

1. Investigate manufacturing cost estimation methods from the academic literature and select a cost estimation model for CNC machining.
2. Develop a manufacturing process planning approach for WAAM based on interviews with experts and academic literature.
3. Develop a cost estimation model for WAAM building on the methods identified in literature.
4. Test the developed cost model using industrial case studies to understand the cost drivers for WAAM.

1.3 Methodology

This chapter describes the research methodology applied in this research. The research methodology is shown in **Figure 2-1**.

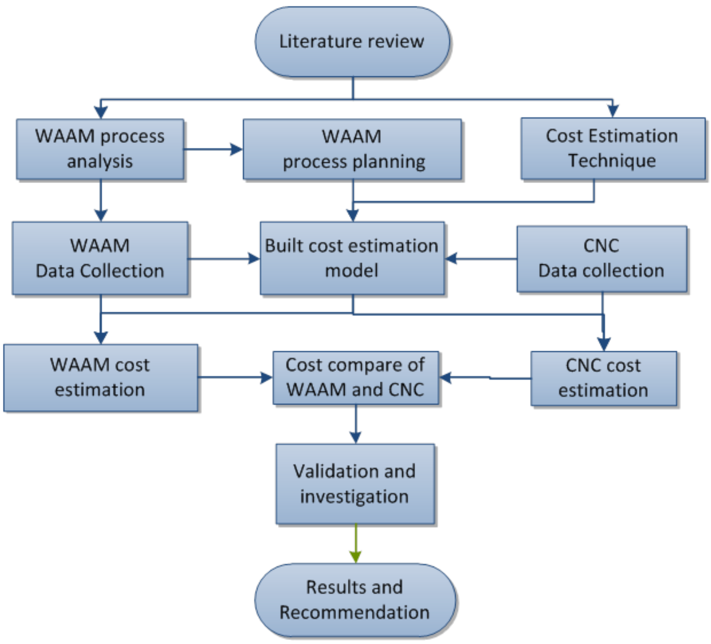

Figure 2-1 Research methodology

Firstly, this research starts with an extensive literature review about AM technologies, process planning activities and cost estimation methods. On the basis of research requirements, Boothroyd's method[7] is selected to build a cost model for CNC machining. According to the principle of Boothroyd's method, a cost estimation model of WAAM is to be developed. A process planning for WAAM is to be built to identify cost drivers of WAAM manufacture process. Following this, an Excel spreadsheet is to be created as part of this research work. In order to compare manufacture cost of WAAM with CNC machining, a costs calculation spreadsheet based on two developed cost models is to be developed.

Verification and validation for developed cost models will be made by experts in Welding Engineering & Laser Processing Centre (WELPC) at Cranfield University. WAAM designers and manufacture experts will review the cost model and process planning, then present suggestions for this research from engineering view point.

After that, A simplified component will be selected for case study 1, the whole investigation will be based on the component to compare manufacture cost of WAAM with CNC machining in batch size, buy-to-fly ratio etc. To investigate cost drivers of WAAM and cost changes with different materials. The results will be analysed.

A more complex and larger part is to be selected for case study 2. This part is a practical aircraft part. On the basis of the part, which manufacture method is more economic will be discussed.

Finally, conclusions and recommendations for this research will be presented.

1.4 Course structures

For AVIC MSc program, the first part of study is English study for three weeks and the second part is the Flying Crane Conceptual Design work, which is a group design project, for 6 months, with the individual research program as the third part. The author involve in the investigation strategic aim of China aviation industry as part of GDP and the results of this work are presented in section 1.6.

1.5 Scope of Thesis

Chapter 1 gives a brief introduction to the background of this thesis including the development of AM, aims and objectives of this thesis. The methodology of this research also is introduced.

Chapter 2 is the literature review about knowledge required in this thesis, including AM, WAAM, process planning and cost estimation.

Chapter 3 is an introduction to a selected cost estimation method for traditional manufacture and a developed cost estimation model for CNC machining is presented in this chapter

In chapter 4, a process planning for WAAM is defined and cost drivers in process planning are analysed.

Chapter 5 supplies a detail introduction to a developed cost estimation model of WAAM.

Chapter 6 introduces a developed cost estimation spreadsheet of WAAM and CNC machining. The validation of cost model is also presented.

Chapter 7 is case studies, which involves using developed cost estimation spreadsheet to estimate the manufacture cost for two parts.

Chapter 8 deals with the results and discussions of this research.

Chapter 9 involves the conclusions of this thesis and some recommendations for future work.

1.6 China aviation industry strategy

This research was done for GDP project that the author attended.

As we all know economic growth is vital for air travel growth, in 2011, China will remain one of the most significant and rapidly growing markets for all sectors of civil aviation. Increasing disposable income and rapid urbanization have led to a three-fold increase in domestic tourism and a five-fold increase in the number of international outbound tourists over the past decade, making China the biggest aviation market outside the U.S.A.

1.6.1 Air transportation demands

From 1995 to 2009, Travel Growth-China's traffic volume grew at a CAGR of 11.8%. China has an increase in travel volume by 167 million by 2020. China aggressively developing travel infrastructure: 38 New Airports, USD46 billion Investment by 2020[8].

On Nov. 16, 2010, COMAC issued a global commercial aircraft market forecast report at Zhuhai Airshow for the first time. According to the report, it is estimated that Chinese market needs more than 3,750 large passenger aircraft by the year 2029[9].

The report also forecasts that 30,230 aircraft and regional jets will be needed in total in the world by the year 2029, including 6,916 double-aisle aircraft, 19,921 single-aisle aircraft and 3,396 turbofan regional jets, and the total value is approximately 3.4 trillion dollars. It is estimated that the global air RFK is increased by 5.2% annually on average, and Chinese RFK takes the first place by the average annual growth rate of 7.7%[9].

1.6.2 The challenges of develop China aviation industry

As we all know, there are many challenges for development of aviation industry.

- First Aviation is an expensive, difficult business, It needs High fixed capital investments.

China's aviation industrial get the strong support from the Chinese government with finance and policy. China has made its commercial aircraft industry development as national priority. As China's Premier Wen Jiabao stated in regard to China's C919 large commercial aircraft project: "The large commercial aircraft] is not only necessary for China's aviation industry, but also necessary for building an innovative country. The research and development of this aircraft will promote the development of science and technology in a number of important areas"[8].

- Second, Airplanes is a long cycle productions. A particular requirement is management challenge; Totally comprehend Customers' present requirements and forecast their future demand is the manger's ability.

From 10th Five Year Plan (2001–2005), 11th Five Year Plan (2006–2010),

To 12th Five Year Plan (2011–2015), China has made long term strategy to support the aircraft industry development. Other correspond policy also developed, namely,

National Medium- and Long-term National Science and Technology

Development Program (2006–2020)— This State Council plan specified the development of large commercial aircraft as one of 16 key industry areas on which China will focus over the next 15 years.

Catalogue Guiding Indigenous Innovations in Major Technology Equipment— this document encouraged the domestic development of 18 types of major technological equipment, to include commercial aircraft[10].

Two companies have the ability to support these policies, one is The Aviation Industry Corporation of China, the other one is Commercial Aircraft Corporation of China Ltd., with the specific goal of developing China's large commercial aircraft project, the C919.

- Third, the Aviation markets are relatively protected despite the ability of aircraft to fly over national boundaries.

This is a global problem which faced by any country, at present, China could be its own best customer, and some airline company also built to support the development. Such as "Joy Air" and "Chengdu Airlines".

1.6.3 The advantages for develop Chinese aviation manufacturing

There are many advantages would support the development of Aviation Manufacturing in China.

- First, the potential big and best customer is China.

Development aviation, China is the biggest customer and do not consider the market. At present, the world's second largest aviation market is in China. In the next 20 years, it is predict that China will spend $213 billion on planes in the next 20 years[11].

- Second, Aviation leads to technological advancement.

A critical advantage to develop aviation industry is that many technologies which used in aircraft can be reused to other areas. As a recent industry report notes, "aviation is a potential technology driver for manufacturing techniques that also pulls along other high-technology sectors such as electronics, advanced materials, and sensors" [10].

Hence, compare the challenges and advantages which shown in china aviation industry, develop the aviation by themselves is a good chance to keep competition in the world.

1.6.4 On-going Aircraft Development Projects

In the past decade, China has made significant progress developing and producing its own aircraft.

Development projects:

The ARJ–21 regional jet:

The ARJ–21 is China's 70- to 100-passenger regional jet program, Canada's Bombardier and Brazil's Embraer are the competitors. The ARJ–21 had its first test flight in November 2008 and is currently in production, there are currently over 200 orders for the ARJ–21, at least 70 percentage come from Chinese state-owned airline companies[11].

In order to ensure that the ARJ–21 has a guaranteed market, Beijing in the past few years established two small, state-owned airline companies that are to fly only domestically produced commercial aircraft. One company, ''Joy Air,'' is a subsidiary of the Aviation Industry of China, while the other, ''Chengdu Airlines,'' is owned by the Commercial Aircraft Corporation of China Ltd. As the table below shows,

ARJ-21 Certification

The US FAA has commenced its technical assessment (shadow program) of CAAC's ability to certify the Commercial Aircraft Corporation of China's (COMAC) ARJ-21 regional jet to international certification standards[11].

The C919 large commercial aircraft:

The C919 is China's premier commercial aviation project. The developer of the C919 is the Commercial Aircraft Corporation of China Ltd, It intends the 150-passenger aircraft to compete with Airbus A320 and Boeing 737 in both the domestic and global markets[11].

The prototype of the aircraft began in August 2010, with an initial delivery scheduled for 2016. Given that China currently lacks the technology and know-how for completing such a difficult project. It's a big challenge for China Aviation Industry[9].

Develop aviation industry is long term process, China should insist on initial aim no matter how difficult it is. During the develop process, China should hold intellectual property right by themselves and develop product by themselves in all main process. This will very beneficial to keep the strategy longer and better.

Based on the market survey, the GDP Flying wing aircraft was designed to be a 200 seat next generation airliner with long range capacity of 7500 nautical miles, designed to most of the major cities from Beijing to London. The strategy made for China aviation industry shows the determination of developing China aviation industry and also make the guarantee to realize the aims.

2 Literature Review

2.1 Additive Manufacture

Additive Manufacture defines a series of technologies which can build physical objects from computer aided design (CAD) files by adding forming material, the definition opposed to subtractive manufacturing methodologies[1]. The component seems like "grow" from nothing to completion. Synonyms are additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication[1; 12].

Slicing the 3D geometric model into 2D layers is the first step of additive manufacture, and the element of each layer is a 2D cross section profile of the part, then, each layer is built in a time and get a near-net-shape component. The process can reduce material, tooling and leading time. Low cost, environment-friendly and geometric flexibility are the advantages of this kind of technologies[1; 12; 13].

All AM technologies share the same layer-additive principle[13] as shown in **Figure 2-1**

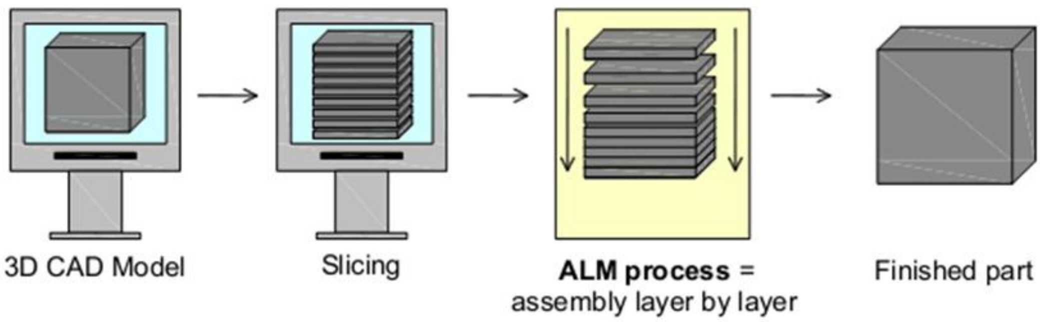

Figure 2-1 Systemic process of AM

2.1.1 Terminology

Originally, AM means prototyping, and now it defines all kinds of technologies that manufacture parts by adding-material. It involves: prototyping, modelling, tool-making, pattern-making and production of end-use parts. AM is used in many commercial areas, therefore, different names emerges for different areas.

Some of them are Rapid Prototyping (RP), Rapid Tooling (RT), Rapid Manufacture (RM), Solid Freedom Fabrication (SFF), 3D Printing etc[1; 12; 13].

Rapid Prototyping (RP)

AM is used to make prototypes, which proved very efficient in reducing the cycles for product development, therefore, the term Rapid Prototyping emerged. The first commercial application of this process is stereolithography developed by Californian company 3D system [1].

Rapid Tooling (RT)

Using AM process to quickly make various tool cores and cavities leads to the term Rapid Tooling (RT). Now, RT process can manufacture a mold on an AM machine directly or indirectly. In a direct process a mold is created on the AM machine, while in the indirect process an AM machine is used to create a master pattern from which a tool is cast and then parts are made [1].

Rapid Manufacturing (RM)

In the late 1990’s and early 2000’s, AM technologies began to be used to create end use products. This led to the term Rapid Manufacturing (RM). Generally, Rapid Manufacture (RM) is widely used in UK and European as the common definition, while Direct Digital Manufacturing (DDM) is used in North American as the common definition[13].

Solid Freeform Fabrication (SFF)

One of the most notable advantages of AM is their ability to manufacture geometries that cannot be achieved by conventional processes. The geometric freedom offered by AM led to the term “Solid Freedom Fabrication (SFF) which is probably the best technical description of the processes. SFF can broadly be seen as a synonym for AM[1].

3D printing

3D printing is known as Additive Manufacturing[1]. As most adding process create parts on a layer-by-layer basis, the process repeats with the subsequent “prints” to create 3D parts instead of 2D profiles, so 3D printing is used to describe the process. Today 3D printing is considered mainly as a reference to low cost machines or those that employ print heads usually for prototyping purposes[1].

2.1.2 Technologies

Many different names for AM can be found in markets. The names are based on different researchers or different companies. How to build each layer is the main difference among these technologies, such as soften or melting. Based on[14] and the author update, different AM technologies and basic materials used are shown in table 2-1**.**

Additive technologies	Base materials
Selective laser sintering (SLS)	Thermoplastic, metals powders
Direct metal laser sintering (DMLS)	Almost any alloy metal
Fused deposition modeling (FDM)	Thermoplastics,eutectic metals
Stereolithography (SLA)	Photopolymer
Laminated object manufacturing (LOM)	Paper
Plaster-based 3D printing (PP)	Plaster, Colored Plaster
Laser-engineer net shaping(LENS)	Almost any alloy metal
3D welding	Almost any alloy metal
Direct metal deposition	Almost any alloy metal
Laser-based additive manufacturing	Almost any alloy metal
3D micro welding	Almost any alloy metal
Electric beam welding (EBM)	Almost any alloy metal
Wire and Arc Additive Manufacturing(WAAM)	Almost any alloy metal

Table 2-1 Basic materials used in some AM technologies[14]

2.1.2 AM technology for metal

Early AM researches focus on physical creation of shape, and not its functionality [1]. Therefore, most of current AM technologies are based on resins and other non-metal material. With the development of AM, Due to the advantages of saving material, no tooling, enhancing complexity of the components, cutting back the cost of manufacturing and environmentally friendly, manufacturing of metallic objects has drawn a significant research interest[2; 12]. Especially for expensive to buy or difficult to machine materials, where waste expect to be minimize[5].

An AM technology can produce near-net shape parts with rough surface accuracy. Hence parts cannot directly used for high precision areas[2; 15]. The reasons of low precision are components split into slices and forming resolutions[2; 6]. In order to solve this problem, two ways introduced to improve accuracy of AM products in dimensions and surfaces requirements[6] which means that parts generally formed in AM machine and accuracy and dimension requirements are meet by milling or grinding machine. The advantages of the process are reducing deposition time and keeping deposition process sustained. In this research, this method is called independent WAAM. The other way is combine AM and subtractive manufacture in one machine, it usually called Hybrid layer manufacturing (HLM) processes by some researchers [2]. The principle of HLM processes[2] is shown in **Figure** 2-2

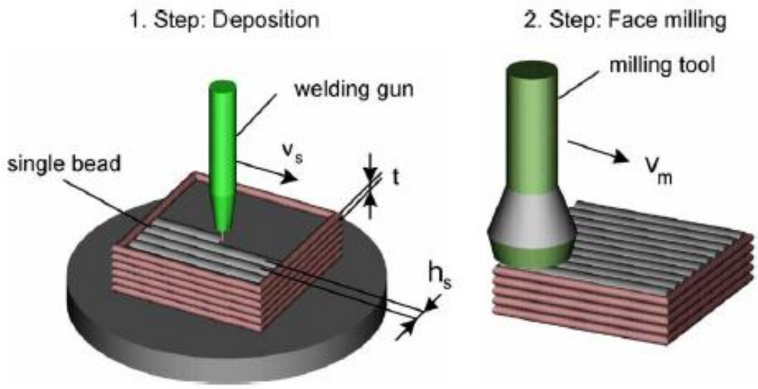

Figure 2-2 Process principle of Hybrid Layer Manufacturing (HLM)[2]

After a layer is built by deposition, the top surface of the layers is machined to get a more accurate layer thickness and a new layer start on the machined layer. After finish deposition, surface finishing operation is applied in the same machine [2]. In this research this method is defined as integrated WAAM in cost model.

K.P.Karunakaran gives the details of integration of HLM in his article[2]. The advantages of this process are decrease machine setup time and transportation time and also can make the process planning arrangement more simple.

2.1.3 Classification of AM processes for metals

The classification for metals AM process has been defined in [2]by K.P. Karunakaran er al. From his views, AM for metal is been divided into direct process and indirect process. When a casting process is involved in layer by layer processes, this kind of AM technologies is called indirect process, otherwise is direct process. According to the material is powder or non-power, direct processes can be further classified into deposition and powder-bed. The classification of AM technologies for metals [2]is shown as **Figure** 2-3

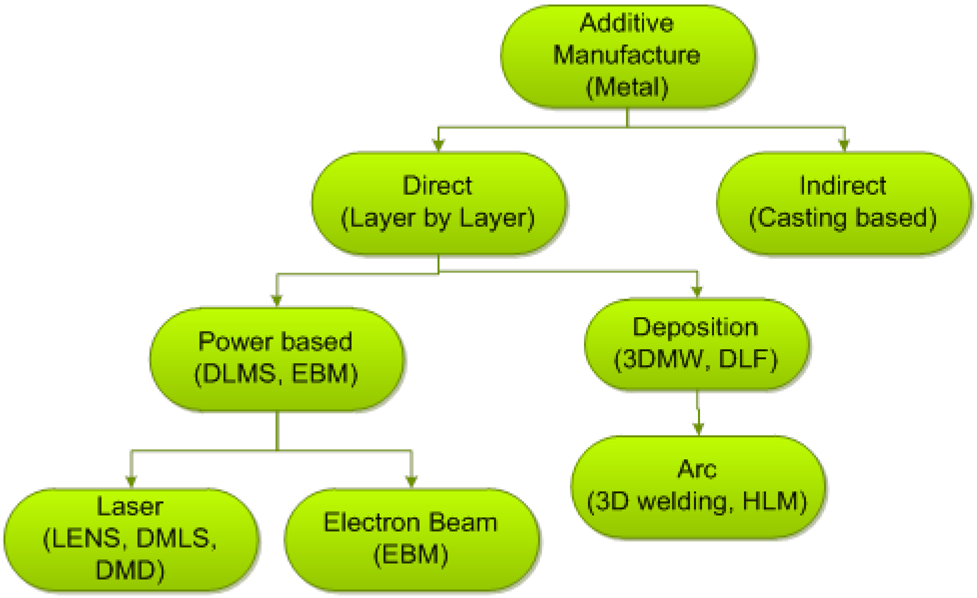

Figure 2-3 The classification of AM metal manufacture [2]

2.1.4 Mechanical properties of AM metal part

Mechanical properties is important for a new product, this will determines the usage of material and technologies. Many researches haven been done to test the mechanical properties of AM part.

An investigation work have been done by Emilie Lorant in[16], an MSc student at Cranfield University to investigate the microstructure effect on mechanical properties of Ti-6AL-4V component made by WAAM and also compare the mechanical properties with annealed wrought Ti-6AL-4V.

In her research, the specimen is manufactured by VBC Interpluse Tungsten Inert Gas Welding, one of WAAM process. Tensile properties, Fatigue Crack Growth Rate and Fracture Toughness properties have investigated to compare the mechanical properties of part manufacture by WAAM and wrought Ti-6AL-4V.

Based on her research, to Young's modulus, Ultimate Tensile Strength and Yield Strength, the part built by AM are similar to values for annealed wrought TI-6AL-4V, and the elongation is smaller for AM specimens tested in the longitudinal direction. The part built by AM show a higher fatigue crack growth rate than wrought Ti-6AL-4V. In this project the specimens tested were 5 mm thick, the fracture toughness values seems similar to anneal wrought Ti-6AL-4V.

Bernd Baufrld et al [17]also made the same research about the Ti-6AL-4V part made utilizing tungsten inert gas welding. In his article "the ultimate tensile strength is between 929 and 1014 MPa. In ASTM, the minimum requirements for cast material a strain at failure of 8% and an UTS of 860 MPa, and for wrought material 10% and 930 MPa".

Based on these two researches, the AM components fulfill at least the requirements for casting material [17][. But compared with wrought material AM parts show a higher fatigue crack growth rate and similar ultimate tensile strength. In order to enlarge the application area, future work should be done to analysis mechanical properties of AM components.

2.2 Process Planning

In product manufacturing system, all aspect of manufacture process such as material, manufacturing process, tooling should be consider at the early stage by the engineer.[18]

The focus of process planning is to determine how a job is to be done and how long it will take[18]. Process planning is an important part of manufacture and almost all the manufacture activities are to be arranged during process planning. So it is possible to analysis process planning activities and use some process planning information to estimate manufacture cost.

2.2.1 Definition

Transform a workpiece from its initial form to a final form according to engineering design is the main work of process planning. The essential function of process planning is shown in Figure 2-4 [18].

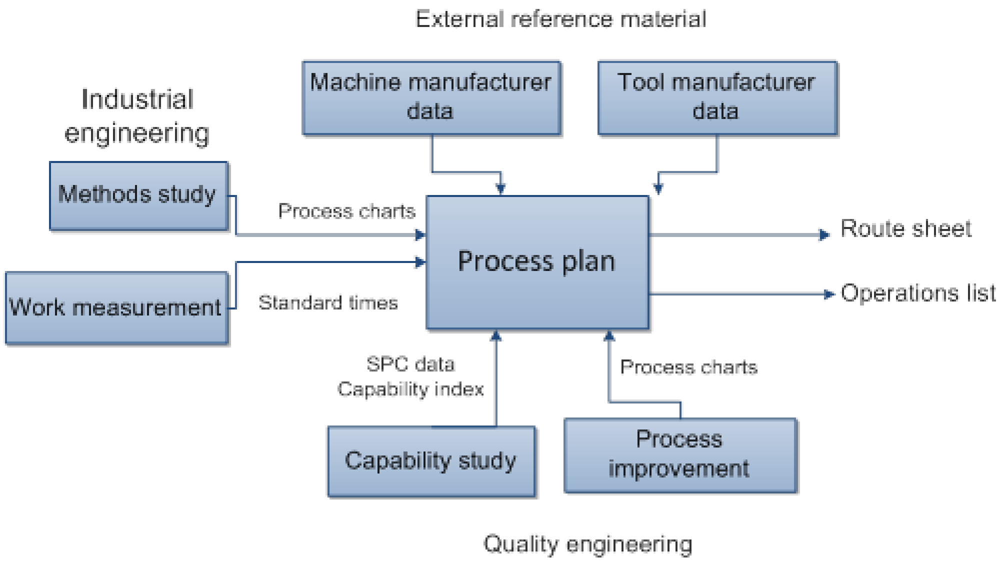

Figure 2-4 Essential function of Process Planning[18]

Process planning is part of production planning. The focus of process planning is to determine how a job is to be done and how long it will take and production planning is more focus on what/when/how/many about the material requirement, capacity requirements, machine requirements, manufacturing scheduling and production execution.

2.2.2 Methods

Manual process planning and computer-aided process planning are two basic methods used in process planning. They can be divided into two distinct approaches respectively[18]. Figure 2-5 shows the basic classification of the methods for process planning[18]:

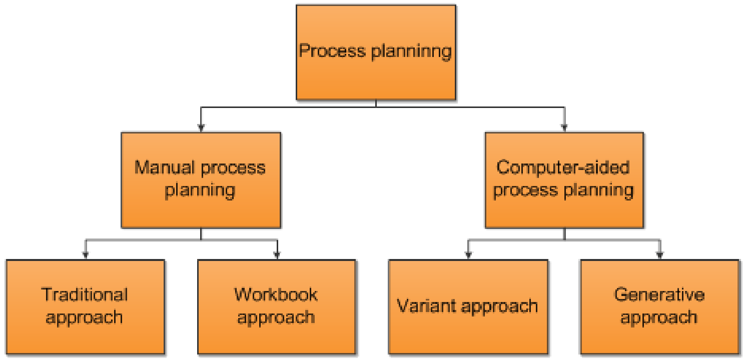

Figure 2-5 Process planning methods[18]

CAPP systems is widely used in process planning, but for WAAM, it is in an development stage and not appropriate to use CAPP. So this research is focus on manual process planning.

2.2.3 Activities

The major activities of process planning show as Figure 2-6

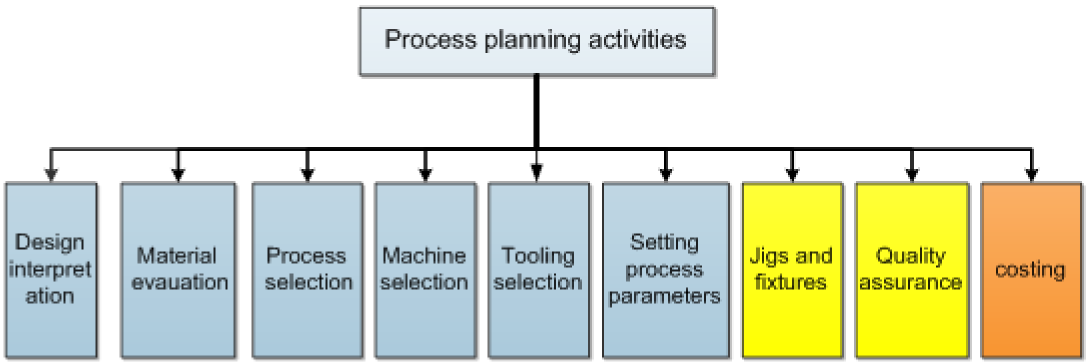

Figure 2-6 Major Activities of Process Planning

The detail of process planning activities is introduced as below, the introduction is based on [18].

- **Design interpretation**

The general information includes component's design are part geometries, dimensions and associated tolerances, geometric tolerances, surface requirements, material specification and batch size etc.. Therefore, to analysis the design information which is provided by designer is the first step of process planning. In WAAM, analysis parts geometries, choosing substrate and slicing 3D model into 2D layers are the major design interpretation works.

- **Material evaluation**

Different material shows different properties in manufacture process. Three main characteristics: shape or geometry; material property and manufacturing properties are used to evaluation materials. For WAAM, designers define which kind of material to be used and process planners need to select appropriate wire diameter according to deposited part geometry.

- **Process selection**

Generally, there are six phases in traditional manufacturing: Preparing the billet - Rough machining - Finish machining - Heat treatment (option) - Finishing operations - Special finishing (option)[18]. In this research, WAAM manufacture process only focus on: preparing the billet, rough forming and finish machining.

- **Selection of machines and tool**

After determined which process is to be used, then manufacturing production equipment must match with selected process. The machine power and torque requirements are determined by part size and weight. In WAAM, there is no power and torque limit for machines and tools selection are also do not need to consider.

- **Process parameters**

Once machining equipment is selected and next step is set process parameters. These parameters are including cutting speed, feed rate and depth of cut to be used for each operation etc.. It also necessary to calculate time taking for each operation[19].

- **Jigs and Fixtures**

The generally low-cost jigs and fixtures are: vices, clamps and abutments, chunks, collets, mandrels, face plates. The process planner is responsible for give specification for jigs or fixtures. In WAAM, the planner do not consider jigs and fixtures, as there is no tooling requirements in WAAM process, however substrate is necessary for WAAM. Generally, substrate is plate. Sometimes, it is very complex according to complexity of parts.

- **Selection of quality assurance methods**

Process planners are also responsible for selecting quality assurance tools and techniques to be used according manufacture process. In this research, quality assurance methods and cost of the quality are not discussed.

- **Economics of process planning**

For a successful product design and manufacture, part manufacturing cost is critical. The final cost of a product including various costs, namely, manufacturing costs, design/R&D costs, overheads (typically marketing, sales, customer services and administration costs) and profit margin. The main cost that process planners concerned on are those related to the production costs and product volumes. Planners will need to make a manufacturing cost estimate for a product and this provided the consult to allow management to determine the potential profitability. Generally, each process can produce part in certain limits of dimensional and geometric accuracy and surface, the tighter of dimension accuracy and surface finishing the more expensive of manufacture cost[18].

2.3 Cost Estimation

Research results shows that over 70% of product production cost is determined during the conceptual design stage [20]. Reduce cost during design stage is the best opportunity to reduce the cost of product. In the design stage, if designer knows the cost of product, then the designer can change a design to achieve proper performance with a reasonable cost. Figure 2-7 shows product costs set and incurred in different phases [20].

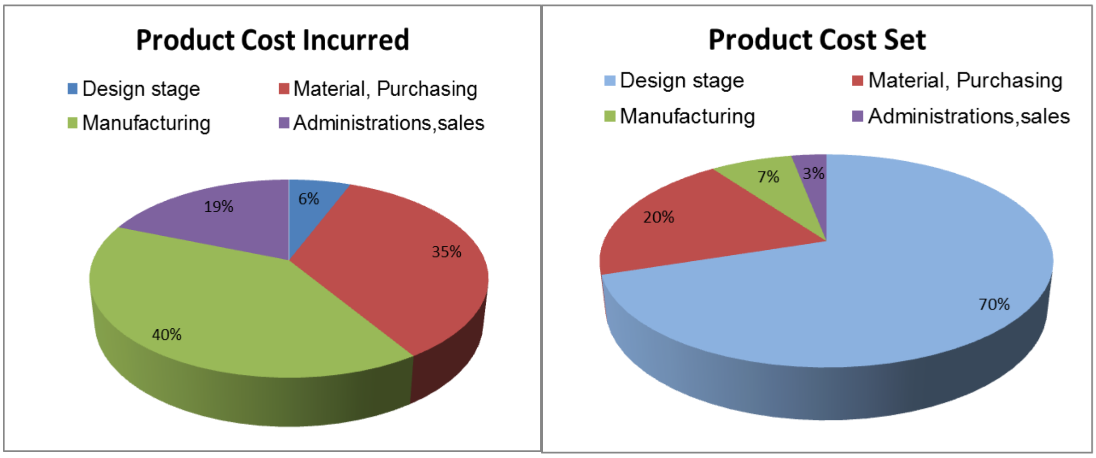

Figure 2-7 Product Costs in Different Phases[20]

An important requirement of cost estimation is accurate. If the result is too high this may lead to loss of business, if the result is too low, this may lead to financial losses to a company.

2.3.1 Functions of cost estimation

In a factory, the aim of cost estimating is to accurately estimate manufacture costs before actually manufacture incurred [20]. Estimated cost is usually used as a datum to create a quote for a customer or evaluate a quote from a customer[19]. The function of cost estimating includes[21].

- Check a quote from suppliers;
- Provided refer for make-or-buy decision;
- Evaluate product design substitutes;
- Support long-term financial planning;
- Assist manufacturing cost;
- Provides standards for production efficiency

In this research, costing estimating is made to help make-or-buy decision for manager and help control manufacturing cost. It also can be used to verify a quote from a supplier or help designer to assess product design.

2.3.2 Introduction of cost Estimation Methods

From an economical point of view, manufacture costs are classified into direct cost and indirect cost. Direct costs connected with a specific part and indirect cost cannot be allocated to a specific part. According to how costs vary with quantity being manufactured, manufacture cost is classified into fixed cost and variable cost. The variable cost will change with number of production, however, fixed cost cannot changed with number of production[19; 21]. From a morphological point of view, the costs are divided into material, labor, engineer and burden costs. In metal machining, more than 50% of the total manufacturing cost is material cost [19]. The product cost structure based on direct cost and indirect [22] is shown in Figure 2-8.

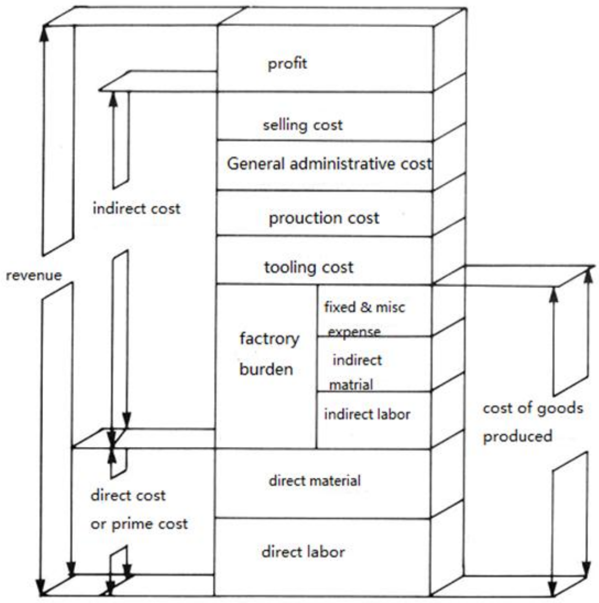

Figure 2-8 Product Cost Structure [23]

In this research, cost model is to be focus on actual manufacture process which is the direct cost such as direct material cost, direct labour cost.

Data collection is important for a cost estimation, because data precise is a critical element for a success cost estimation [20].

Because shape complexity, product accuracy and tooling manufacturing cost will determine total manufacturing cost. Therefore, if all of above information can acquired in early design stage, it is possible to estimate manufacture cost in early design stage [12].

In literature review, a classification of cost estimation method[23] is widely accept by many researchers as illustrated in Figure 2-9

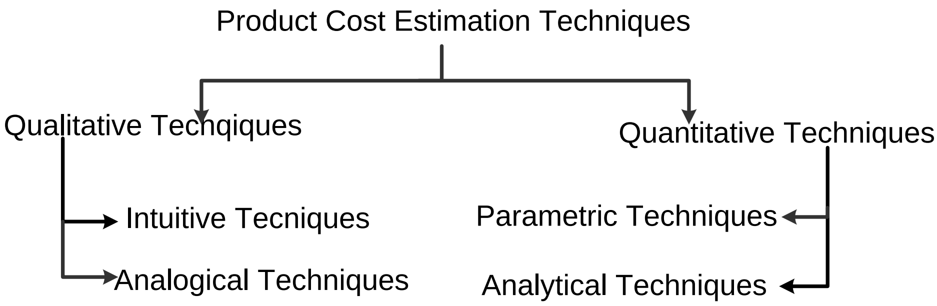

Figure 2-9 A classification of cost estimation techniques[23]

Qualitative Techniques (based on the previously manufactured product)

- Intuitive - based on expert's experiences and knowledge
- Analogical – based on historical cost data, a new product has some degree of similarity with a manufactured product.

Quantitative Techniques (based on a detailed analysis of product itself)

- Parametric – base on using statistical methodologies and identify cost driver.
- Analytical – based on identify all cost resources spend in the production cycle and get cost by add all them together.

A more detailed classification of cost estimation methods is created by Niazi et al.(2006)[23] is shown as Figure 2-10

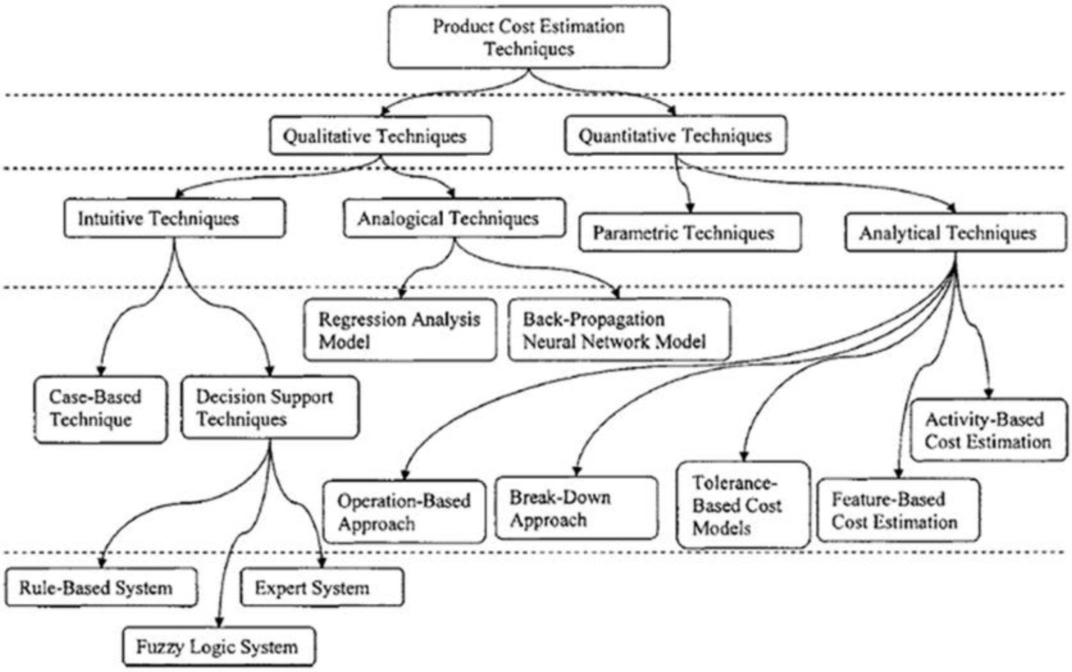

Figure 2-10 A detail classification of cost estimation techniques[23]

2.3.3 Machining cost estimation methods

A number of journals and articles for machined part cost estimation were analysed which focused on quantitative techniques cost estimation. A few of them show as below:

For machined part cost estimation, Jong-Yun Jung developed a manufacturing feature based model to estimate machined part [24], he defined four features in research and provided cost estimation methods for each feature using manufacture parameters, but he did not consider tool replacement cost. David Ben et al. developed an activity-based cost model for design and development stage [19], he identified the activities and total cost for each activity and get final cost of machined part. But this model need too much manufacture details. Li Qian et al [26] developed a parametric cost estimation model based on activity-based costing for rotational parts, this method combine activity-based and parametric method together and can accurate estimate manufacture cost of a rotational part. C.Ou-Yang[26]developed an integrated framework for feature-based early manufacturing cost estimation, this method estimate the manufacture cost of parts according to the shapes and precision of its features.

Boothroyd and Knight developed a cost estimation method which uses volume or weight of part for approximate estimate cost of part in early design stage and relate tool replacement cost to machining cost. The cost involves in this model are material cost, machining cost, setup cost and non-productive cost and almost all direct cost have been considered in this method. This method is one of parametric techniques under quantitative cost estimation method and widely used for traditional manufacture.

The comparison of cost estimation methods is shown in

Table 2-2.

Table 2-2 Cost estimation methods comparison

Name	Method	advantages	disadvantages
Jong-Yun Jung	Feature based	Defines four kinds of feature	Need too much design and manufacture information; No tool replacement cost
David Ben et al.	Activities based	Manufacture activities has been considered	Need too much manufacture information
Li Qian et al	Activities based	More accurate	Only for rotational parts
C.Ou-Yang	Feature based	Combine parts shapes and precision together	Too complex
Boothroyd	Parametric techniques	Few information are needed; simple and wide application area	Ignore manufacturing details

On the basis of comparisons, Boothroyd's method only uses a few information to estimate manufacture cost which can be used in any manufacture methods. WAAM is a new technology and the manufacture process is too complex. Therefore, Boothroyd's method is more appropriate for WAAM. The details of manufacture process can be ignored and build some connections between design information and time consumed.

2.3.4 WAAM cost estimation methods

Limited researches has been done about AM cost estimation, Hopkin[27] developed an approach about small plastic part produced by laser stereo lithography. Ruffo et al.[28] add overheads and investment costs into the Hopkin's research. Ruffo[29]also developed an build time estimator for rapid manufacturing time estimation method for rapid manufacturing. Kiran[30]developed a feature based cost model for WAAM cost model. The feature is simple wall. But his research did not consider substrate cost. He also compared WAAM cost with traditional methods, however, traditional manufacture cost acquired from a supplier not practical manufacture cost.

2.4 Chapter summary

This chapter describes literature review which is an important part of research. WAAM is a good choice for manufacture industries and the superiority involves material reduction, lead time reduction, tooling reduction and cost reduction. Therefore, low cost is a critical dominant position of WAAM. However, It is not yet known when WAAM is cost effective in comparison with other manufacturing process, how to estimate manufacture cost of WAAM and how to compare it with traditional method at the same time is still a problem.

Process planning is important for manufacture which determines how a work is to be done and how long it will takes. Process planners concerned on activities those related to manufacture process. Because most of manufacture activities have been arranged in process planning and time distributions also can acquired in this process. Therefore, it is possible to estimate manufacture cost on the basis of process planning. WAAM is a new process and a common process planning is defined, so it is necessary to develop a process planning and identify all the cost contributions in WAAM.

As mentioned before, cost estimation techniques are divided into quantitative techniques and qualities techniques. Quantitative method is use historical data or similar part and expert’s experience to estimate a new product cost. WAAM is a new manufacture technology and there are no enough experiences and historical data to available. Quantitative techniques are based on detail analysis product and sum up all individual costs together to get all cost. Therefore, this method is more appropriate for WAAM.

Based on the literature review it has been found that:

- There are established cost estimation methods for traditional manufacture process.
- Process planning is well defined for cost resources for traditional manufacture method.
- Limited previous cost estimation & process planning for WAAM with researches in cost estimation.
- Cost effectiveness of WAAM is difficult to evaluate

Therefore, it is necessary to develop a cost estimating model for WAAM in early design stage and identify the cost drivers of WAAM. It is also essential to find a method capable of providing manufacture cost comparison of WAAM and CNC and this will fill the gap which was found in literature review.

3 Development of a CNC cost estimation model

Many cost estimation methods for machined parts have been developed by different researchers. It seems like to me that Boothroyd's method is the most appropriate one for this research. This method uses limited information to calculate manufacture cost and most of the data can be acquired in the design stage, so it can be used in the early stage of design. Nearly all the cost distributions in manufacture process are considered in Boothroyd's method. It can make a quick estimation and is very important for WAAM, because there is no enough history manufacture data available. The details about Boothroy's method are as follow.

3.1 Boothroyd's cost estimation method

Boothroyd's method is widely used for cost estimation of a machined part cost in the design stages. This method can be used for machining process, namely, turning, milling, grinding, reaming, drilling etc. and one of advantages of this method is that not much information is needed. The required information includes machine hourly rate, operator hourly rate, volume of machined material, tooling material, set-up time, non-productive time. The details of Boothroyd's method can found in book[7], page 476-501.

The principle of this method is shown in Figure 3-1:

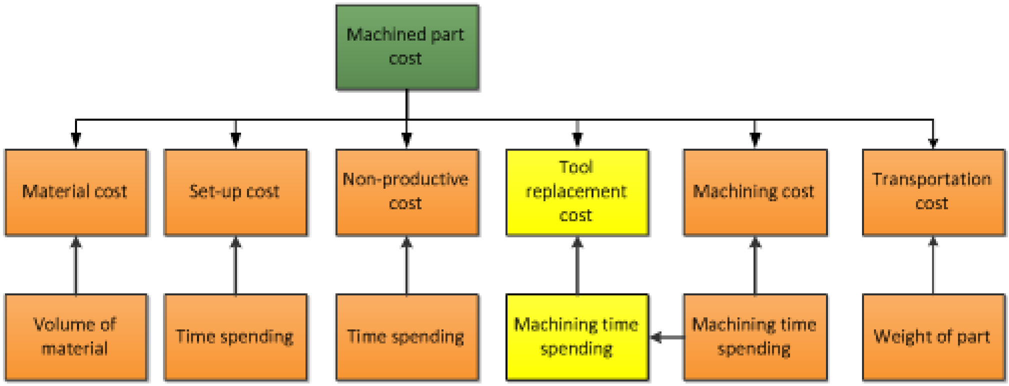

Figure 3-1 The principle of Boothroyd's cost estimation method

In this method, manufacture cost of a machined part is divided into six parts. This method considers all direct costs in manufacture process, with the aim of establishing a connection between machine & operator hourly rate and time contributions in manufacture to estimate actual manufacture cost.

3.2 Development of CNC cost model

One of aim of this research is to compare manufacture cost of WAAM with CNC machining, therefore, it is necessary to develop a cost estimation model for CNC machining and adapt Boothroyd's method to suit CNC machining.

3.2.1 Assumptions

Based on Boothroyd's method some assumptions have been made for developing a CNC cost estimation model.

- Material limitation:

At present, the materials used in WAAM is titanium, aluminium and steel, hence, the material in CNC cost estimation model are limited in these three materials.

- Machining process

CNC machining process usually is divided into rough machining and finish-machining. In rough machining, the maximum power condition is applied for cutting operation and rough machining time is determined by volume of removed materials, so an assumption is made that the material to be removed is machined away in rough-machining.

Finish-machining follows rough machining and it is not closely associated with metal removal. Few material needs to be removed in finish-machining so finish-machining time is determined the requirements of dimensional accuracy and surface roughness. It is assumed that generated surface area in finish-machining is the same as all surfaces of a final part.

- Transportation cost

In Boothroyd's research, as an example, a workpiece weighing 10lb, the effective transportation time for the workpiece is only 1.6s, so it can be neglected compared with other time contributions in manufacture process. Therefore, transportation cost excludes in CNC machining cost model.

- Number of operation

Number of operation is defined as the number of times which a component needs to be re-clamped in manufacture process or the tool needs to be replaced in operation process. Number of operation affects non-productive time.

Besides above assumptions, the principle of CNC machining cost estimation model is the same as Boothroyd's method.

3.2.2 Equations in developed CNC cost estimation model

On the basis of Boothroyd's method and some assumptions for CNC machining, a CNC machining cost estimation model has been developed. This model is an adapted version of Boothroyd's method. The equations and details of the cost model are as below:

3.2.2.1 Material cost

Material cost is the cost of raw material and is generally called billet cost. Billet cost can be more than 50% of the total cost[7]. Accurate figure for volume of material can be obtained from a planner. The biller size is the maximum size of part plus some excess. Material cost can be defined as mass of material multiplied by the material price in market. It should be notice that material price changes with market. So material cost can calculated as below:

$$C_m = V_b \times \rho_m \times C_{m/kg} \tag{3-1}$$

Where:

C_m = material cost

V_b = Volume of billet

ρ_m = Density of material

$C_{m/kg}$ = Cost of Material

3.2.2.2 Machining cost and tool replacement cost

The machining cost is incurred between engagement and disengagement of feed[7]. Every time a tool needs to replaced due to wear, two cost are incurred:(1) while a operator replaces the worn tool, the cost of machine idle time will be incurred, in addition to the (2) cost of a new cutting edge or tool.

For machining when neglecting the non-productive time, considering tool replacement cost. The cost of machining a feature in one component on one machine tool can be expressed by below an equation adapted from[7] shown as follows:

$$C_{m-t} = (R_m + R_O) \times t_m + \frac{Q \times ((R_m + R_o) \times t_{ct} \;\; + c_t) \times t_m}{t} \quad \textbf{(3-2)}$$

Where:

C_{m-t} = Machining and tool replacement cost

R_m = Machine hourly rate

R_o = Operator hourly rate

t_m= Machining time(time the machining tool is operating)

Q = Proportion of t_m for which a point on the tool cutting edge is contacting the workpiece.

t = Tool life while the cutting edge is contacting the workpiece

t_{ct}= Tool-changing time

C_t = Cost of providing a new cutting edge

Consider tool life t is given by Taylor's tool-life equation, make some substitution and consider machining power condition, equation (3-2) is converted into equation (3-3) and (3-4), the details show in[7].

- **Optimum power condition machining cost (finish-machining):**

Machining cost is minimum one in optimum power condition, therefore, an assumption is made that optimum power condition is applied in finish-machining. A cost estimation equation (adapt from book[7]) for finish-machining is shown as follows:

$$C_{fm} = \frac{t_{mc}}{1-n} \times (R_m + R_o) \tag{3-3}$$

Where:

C_{fm} = Finish-machining cost

t_{mc} = Machining time when the optimum cutting speed is used

n = Taylor tool-life index, it is dependent mainly on the tool material.

For high-speed tools n is assumed to be 0.125 and for carbide tools, is 0.25

R_m = Machine hourly rate

R_o = Operator hourly rate

- **Maximum power condition machining cost(Rough-machining):**

Because of power limitations, always using optimum cutting conditions is not possible and cutting speed is limited by the power available. In CNC machining cost model, just assuming that maximum power condition machining is applied in rough-machining and all excess materials are removed in rough-machining. Cost estimation equation for rough-machining is shown as follow and the equation is adapted from [7]:

$$\boldsymbol{C_{rm}} = (R_m + R_O) \times t_{mp} \times [1 + (\frac{n}{(1-n)}) \times (\frac{t_{mc}}{t_{mp}})^{\frac{1}{n}}] \tag{3-4}$$

Where:

C_{rm} = Rough-machining cost

t_{mp} = the machining time when the limited power speed is used

t_{mc} = Machining time when the optimum cutting speed is used

R_m = Machine hourly rate

R_o = Operator hourly rate

n = Taylor tool-life index, it is dependent mainly on the tool material.

For high-speed tools n is assumed to be 0.125 and for carbide tools, is 0.25

- **t_{mp} and t_{mc} calculation equation**:

t_{mc} is the corrected machining time considering tool replacement cost when optimum power is available. It used to calculate the finish-machining time. t_{mc} can be calculated by the follow equation which is adapt from [7].

$$t_{mc} = \frac{60 \times A_m}{Vf} \tag{3-5}$$

Where:

t_{mc} = Machining time when the optimum cutting speed is used

A_m = Surface of part machined in machining operations

vf = surface generation rates

The machine surface generation rate is related to the part material and cutter material and this data can be acquired from machinery data handbook[31].

t_{mp} is the corrected machining time considering tool replacement cost when maximum power available and it used to calculate the rough-machining time. t_{mp} can be calculated by the follow equation which is adapted from[7]

$$t_{mp} = \frac{60 \times V_r \times P_s}{P_m} \tag{3-6}$$

Where:

t_{mp} = the machining time when the limited power speed is used

V_r = Volume of material to be removed in machining operation

P_s = Unit power of machine

$P_m =$ Maximum power of machine

Machine unit power can acquired from machinery data handbook[31] and machine available power can acquired from Boothroyd's book[7].

The cost of machining and tool replacement is decided by the cutting condition. Generally, machining process is comprised by optimum power condition and maximum power condition. Optimum power condition is the minimum cost of machining and the maximum cutting speed is used. It is reasonable that optimum power condition is applied in finish-machining because few materials are to be removed. In this condition the tool cost is larger because cutting speed is very high. For CNC machining, most of material is machined away in rough-machining, so it is recommend that reducing cutting speed because this would reduce the tool cost in rough-machining. Therefore, using maximum power condition in rough machining is reasonable.

3.2.2.3 Set-up cost

The set-up cost is determined by set up time contributions. The suggested set-up time can be found in [7].The set-up time mentioned in this research is for batch of parts and not per part, therefore, set-up cost would change with the number of manufacture. The set-up cost can be calculated by set-up time is multiplied by operator hourly rate add machine hourly rate. The equation is shown as below:

$$\boldsymbol{C_s = t_s \times (R_m + R_o)} \qquad \textbf{(3-7)}$$

Where:

C_s = Set-up cost

t_s = Set-up time

R_m = Machine hourly rate

R_o = Operator hourly rate

3.2.2.4 Non-productive cost

Non-productive time costs incurs in every operations which carried out on one machine tool. It includes loading and unloading time, tool engagement and disengagement time etc. Non-productive time is changing with operations changes, the operation changes includes turn-over part, cutter change, so number of operations is selected to calculate non-productive time. Non-productive cost can be calculated by below equation:

$$\boldsymbol{C_n = t_n \times (R_m + R_o) \times N_{op}} \quad \textbf{(3-8)}$$

Where:

C_n= Non-productive cost

t_n = non-productive time

N_{op} = Numbers of operations

R_m = Machine hourly rate

R_o = Operator hourly rate

3.2.2.5 Total CNC machining cost

The total CNC machining cost can be calculated by follow equation:

$$\boldsymbol{C = C_m + C_{m-t} + C_s + C_n} \quad \textbf{(3-9)}$$

C = CNC machining cost

C_m = material cost

C_{m-t} = Machining and tool replacement cost

C_s = set up cost

C_n = non-productive cost

Volume of materials to be removed, surface generated are process input information in the cost model which are determined by the designer. Machine and cutter input information which can be obtained from machinery data handbook[32]. The CNC cost model integrates tool replacement cost into actual manufacture cost and the users do not need to know the details of a cutter. CN machining condition is divided into rough-machining and finish-machining. Removed material is used in rough-machining and generated surface is used in finish-machining. These factors are used to estimate machining cost and tool replacement cost. The cost model can be straightforward used to estimate cost of a part machined by CNC machining at the early design stage.

3.3 Chapter summary

The essence of a cost model is use limited information to predict the potential cost of process. Boothroyd's method suggests that considering some common costs aspect of manufacture can lead to a valuable cost results to customers or managers. A cost estimation model for CNC machining has been developed.

One of purpose of this research is compare the manufacture cost of WAAM with CNC machining and the principle of Boothroyd's method is time distribution and manufacture process analysis. For WAAM, there is no enough history data available and the important aspect of build WAAM cost model is identify cost drivers of WAAM and understand manufacture process of WAAM. So, next chapter is to be defines a process planning for WAAM.

4 Process planning for WAAM

Adapting Boothroyd's method suit WAAM, it should be noticed that an important factor in this method is time distributions in manufacture process. Many studies have been carried on time spending in CNC machining and there are large of history data available in cost estimation. However, WAAM is a new manufacture method and limited researches have been carried out on time distribution estimation and there is no history data available, therefore, the following work of this research is to define a process planning for WAAM and analysis cost drivers of it.

4.1 General Introduction

Processing planning is important for manufacture process. The focus of process planning is to determine how a work is to be done and how long it will take[18]. WAAM is an AM technology carried out at Cranfield University, therefore, this research is focus on the equipment and technologies applied at Cranfield University.

Similar research works have been done at Cranfield University. Kiran[30] has developed a feature based model for WAAM and her study was based on the wall width of deposited weld structure. Jianing Guo[32]is developing more features to calculate cost of WAAM and he is more concentrating on the details of WAAM itself.

A generic process for AM [1]is shown in Table 4-1. Costs of last four steps are to be considered in WAAM cost model.

Process step	Description	cost
Convert CAD model to STL format	CAD model is converted into STL format	No
Product planning	Planner use experiences to select best orientation for example to minimize build time or to achieve tolerance on key dimensions, the deposition sequence of the part, datum for machining operation	No
Create slice files	Software generates program to slice the 3D model to 2D profile.	No
Create substrate	The dimension and material of the substrate will be selected	Yes
Fabricate part	2D profiles are sent to the machine to drive part creation, and part deposited.	Yes
Post-process	When parts have been fabricated they need to be cleaned, to remove from the substrate	Yes
Finish process	Grinding or milling the part to required accuracy.	Yes

Table 4-1 A generic process of AM [1]

4.2 A developed process planning for WAAM

4.2.1 A process planning flow chart for WAAM

Figure 4-1 shows a general process planning flow chart for WAAM and it contains nearly all necessary activities in manufacture process from 3D data input to delivery final part. Manufacture costs which are to be considered in cost model have been identified in **Figure 4-1**. Some costs which are not considered in cost model are determined by the ability of a planner and it is too flexible to estimate.

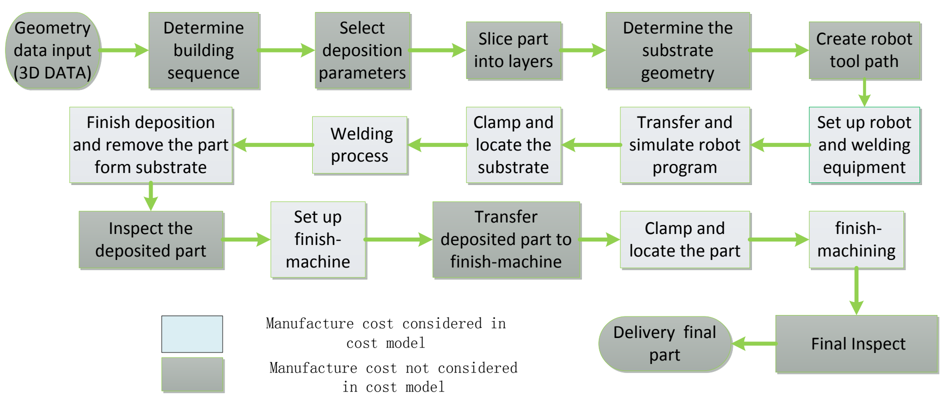

Figure 4-1 A process planning flow chart for WAAM

4.2.2 Investigation of process planning activities in WAAM

All necessary operations incur in WAAM are shown in **Figure 4-1**. This flow chart is been created on the basis of knowledge obtained from literature review and discussion with experts in WELPC. The follow steps of research are analyze the activities in WAAM process planning.

4.2.1.1 Design interpretation

In WAAM, design interpretation includes slicing 3D part into 2D layers and generating ready-to-use tool path code for robot. A robot path generation program RUAMROB has been developed based on Matlab 7.1 and it is used to slices part and generates robot code. The program RUAMROB also has the ability to translate program from ASCII format into binary format which can be executed by the robot [5; 6].

Analysing geometry of parts, choosing appropriate building orientation and determining building sequence are very critical to a successful process planning. A planner can determine slicing directions and number of layers. A good design interpretation can help to minimize build time and achieve required tolerance on key dimensions and reduce material wastage.

4.2.1.2 Material evaluation

There are two materials to be considered in WAAM. One is deposition material, material. The other one is substrate material. Deposition material is filler wire which is determined by designer. However, a planner has the authority on choosing the diameter of filler wire. The commonly used filler wire are 0.8mm, 1mm and 1.2mm. 0.8mm and 1mm is very brittle and 1.2mm is most popular size which shows very good welding quality in aerospace parts application. Titanium, aluminum and steel are the only material used in WAAM at present, therefore, it is necessary to enlarge material application area for the more widespread use of WAAM.

Substrate material is a special characteristic of WAAM. Substrate acts as the basement in WAAM which is applied to support and locate deposited part. After a planner analyse the geometry of a part and volume of the substrate can be determined at the same time and volume of material is determined by the geometry of locating surface. On the basis of experiences provided by welding experts that a 20mm excess is to be needed in clamping edge of substrate. In this research, two kinds of substrates are defined, one is complete substrate and one is partial substrate, if all of substrates are removed after deposition, then, this kind of substrate is called complete substrate; if only partly substrate are removed after deposition, then, this kind of substrate is called partial substrate.

In order to reduce deformation in deposition process that substrate material usually is same as the part. Most of substrate is applied once, however, sometimes, the substrate can be reused, that means, after finished deposition substrate are removed and the surface of substrate needs to be grinding or milling in order to maintain the flatness of support surface, then reuse it. On this occasion, material cost of the substrate can be ignored.

Generally, the geometry of substrate is a plate. However, when parts are very complicate which makes substrate are very complex and needs to be manufactured before using. In this situation, machining cost of substrate has to be added into total cost of WAAM. The substrate manufacture cost can be calculated by Boothroyd's methods or the developed CNC machining cost estimation model.

4.2.2.3 Process selection

For the purpose of meeting required surface or dimension accuracy of parts and a finish-machining process usually arranged after deposition process. The common process for WAAM is: prepare wire - deposition - finish-machining. Deposition process is the welding process which can produce near-net shape part by adding material[1]. As discussed in literature review, currently, there are two methods to realize manufacture requirements. One is independent WAAM, the other one is integrated WAAM. In independent WAAM, deposition process is carried out by robot controlled welding equipment and deposited parts are transported to finish-machining machine (grinding or milling).In integrated WAAM, the deposition process is combined with finish-machining process and welding torch is installed in CNC machine. After deposition, the finish-machining to start directly without transport deposited parts. Other process arrangement such as heating or special treatment is decided by design requirements and this part of cost not include in WAAM cost model.

4.2.1.3 Machine selection

There are two type machines used in WAAM. One is welding machine and the other one is finish-machining machine. Figure 4-2 shows an independent WAAM machine used at Cranfield University, welding torch is guided by a 6-axis Fanuc Robot**Figure 4-3**. In this system deposition and finish-machining is done by two machines: welding robot and CNC or grinding machine[6]. **Figure 4-3** shows an integrated 5-axis grinding system used in Cranfield University. In this system, welding machine is integrated into finish-machining machine (CNC machine or grinding machine)[2] and deposition and finish-machining process are done in the same machine which would reduce setup time in manufacture process.

Figure 4-2

An independent WAAM machine

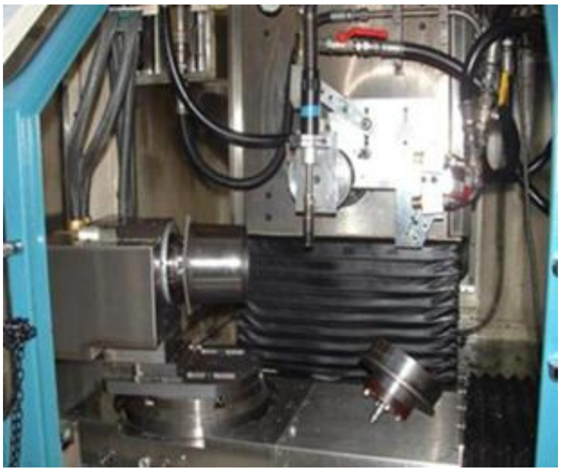

Figure 4-3

An integrated WAAM machine

4.2.1.4 Setting process parameters

In deposition process, there are many parameters need to be considered, in terms of wire feed speed, travel speed, waiting and cooling time etc.

Wire feed speed and travel speed

Wire feed speed determines deposition rate and travel speed guides welding torch to form geometry of parts. On the basis of researches [33], before slicing the 3D model, deposition parameters should be set first, namely, travel speed, wire feed speed and ratio of deposition WFS/TS. Initially, the author thought it was not reasonable to estimate deposition time only using wire feed speed. After did some researches and discussed this problem with researchers in WELPC at Cranfield University and the author realized that keep the ratio of WFS an TS is a constant can avoid erratic and ensure good quality and uniformity of welding beads during welding process[6].by means that, WFS and TS can change each other. The relationship of WFS, TS and wall width [34]had been developed by the researchers at Cranfield University. Figure 4-4 shows the relationship between WFS, TS and wall width for 1.2mm steel wire. The figure shows that wire feed speed can determine deposition time and the ratio of WFS/TS ensure good quality and uniformity of welding beads avoiding erratic[2]. Once wire feed speed is selected and travel speed is determined indirectly. The volume of deposited material for one layer has been decided, therefore, the total volume of deposited material is divided by the volume for one layer and get the number of sliced layers. So it is reasonable that using wire feed speed is to calculate deposition cost.

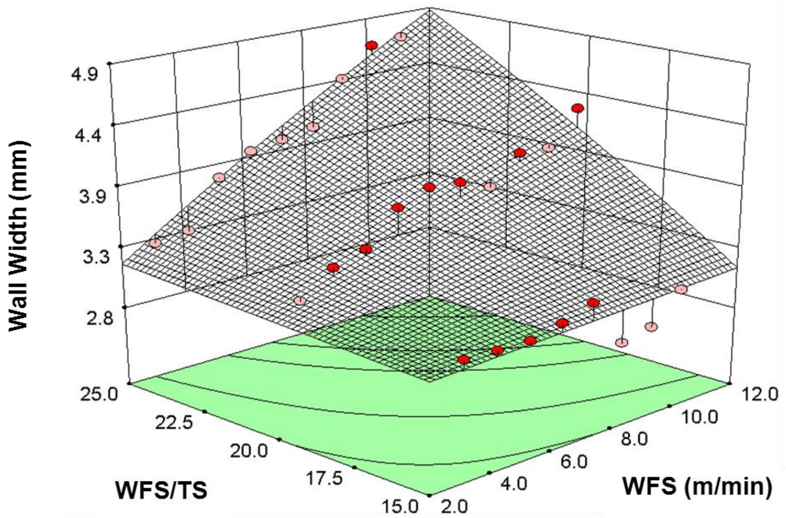

Figure 4-4 Empirical Process Model[34]

Cooling and waiting time

In WAAM process, the heat input cannot avoid and distortion and residual stress are incur in manufacture process [33]even for cold metal transfer which is a low heat input process compared with other WAAM technologies[33]. In welding process, cooling and waiting time are necessary, especially for small or compact parts. After one layer finish welding, a waiting time is set to wait formed beads cool down enough to start a new layer welding. The waiting time is determined by the geometry of parts and material type. The normal waiting times are two or three seconds. If a part is large enough or several parts are deposited together like nesting. The nesting process is shown in **Figure 4-5**, in this case, cooling time can be ignored because there are enough time for cooling in welding process.

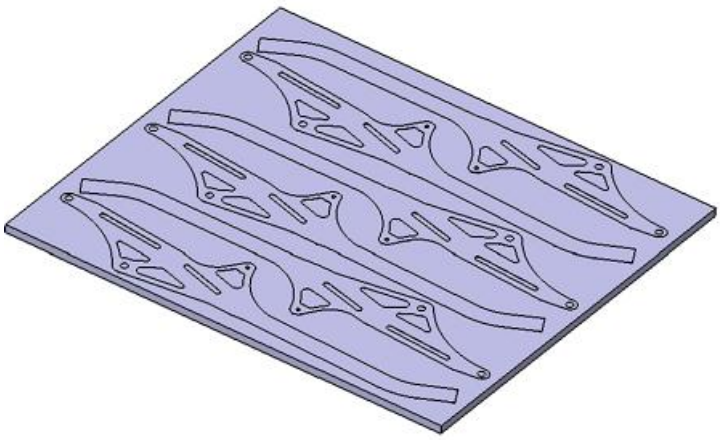

Figure 4-5 Nesting part on one plate

All above mentioned issue indicates that actual part build rate is slower than deposition rates due to manipulation time, in terms of cooling time, waiting time and reverse time or other time distributions. So in cost estimation model this part of time should be considered. Cooling time is related to part geometry and it is difficult to estimate. It is also related to welding time and can be seen as part of non-productive time.

Process parameters are critical for welding quality, Yong –AK Song [35]made a detail introduce about the influence of parameters. He use on welding quality, The result shows that, the voltage of welding and wire feed speed has significant influence on bead width, however, the shielding gas composition shows a small influence. For welding spatter, the wire feed speed also shows a high impact on welding spatter formation, whereas the shielding gas composition shows very little influences. His research express that, "the relative orientation of the deposition beads to the load direction determines the tensile strength of deposited structures". Therefore, it is suggested that set to alternating deposition by 90˚ after each layer.

4.2.1.5 Jig and fixtures

There is no tooling requirements in WAAM, so the cost of jigs and fixtures designing and manufacturing can be reduced in cost estimation compared with traditional manufacture. This part of cost is excluded in WAAM cost model.

4.2.1.6 Quality assurance

A process planner is responsible for appropriate quality assurance tools and techniques to be used in manufacture process. After deposition, a CMM is used to inspect near-net shape parts. The part inspection method is same as traditional manufacture in finish-machining. The quality assurance methods and cost of quality are not discussed in this research.

4.2.1.7 Costing

For a successful product design and manufacture, manufacturing cost is critical. The main cost of a process planner concerned on those related to the production costs and product volumes. The planner is to be compile a manufacturing cost estimation for a product to allow managements to determine the potential profitability of the product. In WAAM there are some special costs that need to consider when estimating manufacture cost.

- **Shielding gas**

Shielding gas is a special characteristic of WAAM and it is very necessary in order to keep a stable welding operation and protect weldment from atmosphere contamination[36]. Argon and Helium are the common used gas. Different welding materials need different shielding gases. Argon and Helium mixtures are the most “security” gas and compatible with all types of material[36]. Different mixture of gas shows different cost, so shielding gas cost need to be considered in WAAM cost model

- **Wire change cost**

This activity is not always incurs in the welding process. If a part is larger and a roll of wire is used out, then, the operator needs to change a new roll wire in welding process. When changing wire, two costs incurs, one is new wire cost which has been calculated in material cost, the other one is machine idle cost which is determined by wire change time and wire change frequency. When calculating the manufacturing cost, the wire change cost need be considered in WAAM cost model.

- **Re-location during deposition**

Compared with CNC machining, it is more difficult for WAAM to re-locate a part when a turn-over operation is needed because the robot cannot find the datum point automatically. After turn-over the part, the planner needs to re-located part and defines a new datum in another side and this will increase the set-up time. So in WAAM, when a part needs turn-over in deposition process and set-up time is to be change with turn-over frequency.

4.3 Chapter Summary

Based on above analysis about activities incurs in WAAM process planning and the cost drives of WAAM have been identified. Analysed all the operations in WAAM process planning and on the basis of the principle of Boothroyd’s method, the cost elements of WAAM breakdown is shown in Figure 4-6**.**

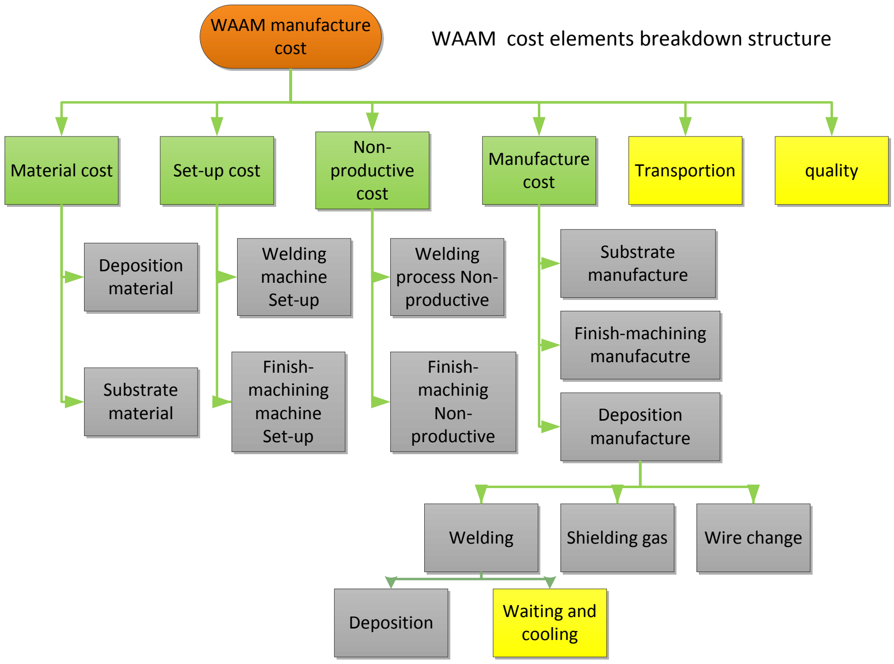

Figure 4-6 WAAM cost elements breakdown structure

Cost driver in WAAM have been identified and data collections have been made, the next work of this research is to develop a cost estimation model For WAAM.

5 Development of a WAAM cost estimation model

A WAAM cost estimation model has been developed in this research which applies limited design information and process planning parameters to estimate the manufacture cost of WAAM.

5.1 The principle of cost model

On the basis of analysing of WAAM manufacturing process and cost estimation principles introduced in Boothroyd's book[7]. A cost estimation model of WAAM has been developed. The principle of cost estimation model for WAAM is shown in **Figure 5-1**.

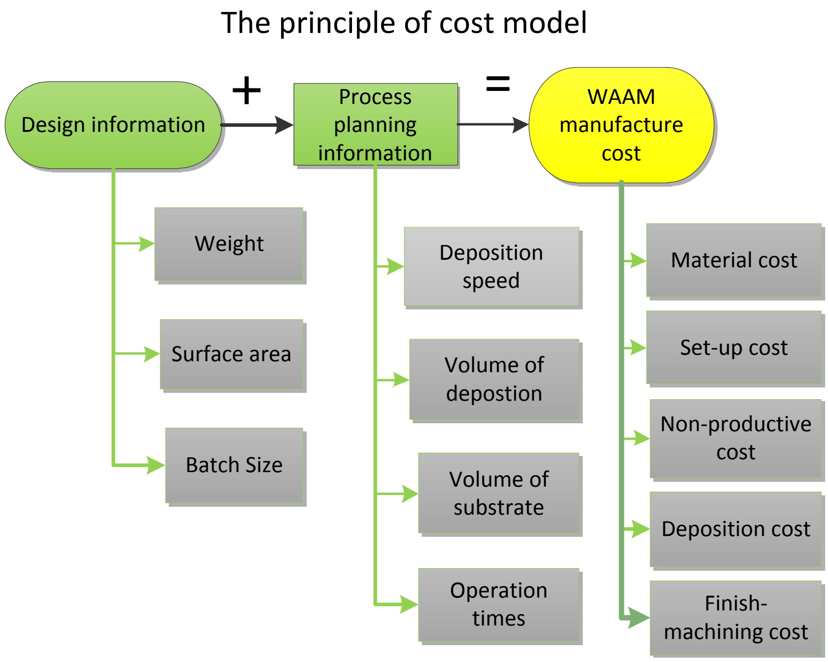

Figure 5-1 The principle of WAAM cost estimation model

5.2 Development of WAAM cost estimation equations

In the cost estimation model, WAAM manufacturing cost is comprised by deposition cost and finish-machining cost. Deposition process builds near-net shape parts and finish-machining process produces required surface and dimension accuracy of parts.

5.2.1 WAAM material cost

In WAAM manufacture, material cost is comprised by deposition material cost and substrate material cost.

- **Deposition material cost**

Deposition material cost is volume of deposited materials and the term part build efficiency is to be mentioned in calculating process. Part build efficiency is same as alloy efficiency in some articles and part build efficiency is select to instead of alloy efficiency in this thesis. WAAM can produce near-net shape parts and parts build efficiency reflects how much of deposited structures which have to be removed in order to meet the final dimension requirements. Two kinds of definition of part built efficiency were found. Kiran[30] in her thesis called part built efficiency as alloy efficiency, the definition based on Figure 5-2:

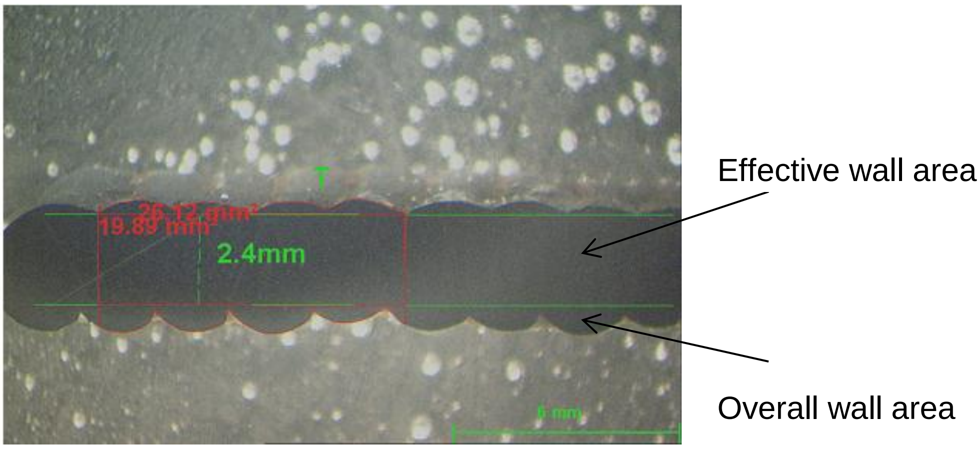

Figure 5-2 CMT MIG weld wall section[31]

Part build efficiency in percentage = $\frac{Effective\ wall\ area \times 100}{Overall\ wall\ area}$, and he also used a material wastage factor 5% to add the material wastage on top surface of the wall, in his opinion, “a material factor has to been considered because some of the material need to trimmed off at the top surface of the wall since the surface of the top most weld layer is never smooth”. However, Mattias[37] give another definition for part build efficiency, in his thesis, his definition based Figure 5-3

In his thesis, “part build efficiency reflects how much of an original structure that had to be removed in order to get a final sample, part build efficiency is calculated by: Usable Area/Total Area.”

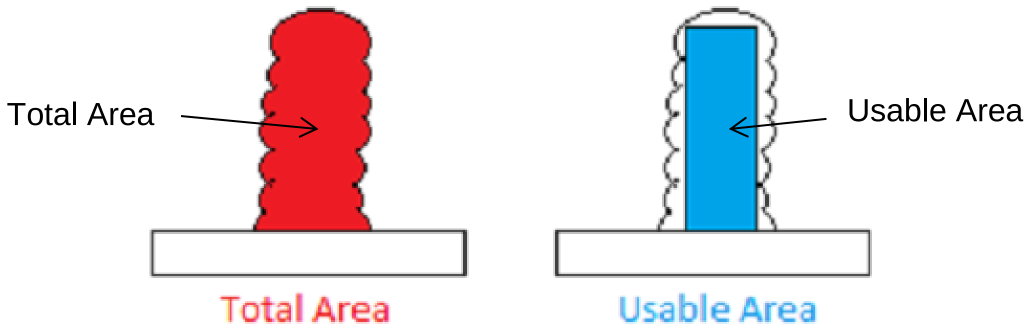

Figure 5-3 Measurement of part build efficiency[37]

Mattias’s definition from an entire point of view, therefore, part build efficiency definition discussed in Mattias’s thesis is used to calculate the cost of deposition materials in WAAM cost model. The usable volume is the volume of final part and total volume is the total volume of deposited materials. Part build efficiency is affected by different materials and different process parameters. Normally, default value for part build efficiency is 80%. Filler wire cost can be obtained from material suppliers.

Deposition material can be calculated by equation shown as follows:

$$C_{dm} = \frac{V_{dm} \times \rho_{wire}}{E_p} \times C_{wire} \quad \textbf{(5-1)}$$

Where:

C_{dm} = Deposition material cost

V_{dm} = volume of deposition (not always equal to volume of final part)

ρ_{wire} = Density of filler wire

E_p = Part built efficiency

C_{wire} = Filler wire metal cost

- **Substrate Material cost**

Substrate material cost is a special material cost of WAAM which is determined by process planning arrangement. Generally, there are two kinds of substrates one is complete substrate, one is partial substrate. If all the substrate are removed away after deposition and this kind of substrate is defined as complete substrate; If only some of substrates are removed after deposition and this kind of substrate is defined as partial substrate. The geometry of substrate is defined by a process planner and the excess for clamping should be considered. On the basis of experts' experiences in WELPC at Cranfield University, a 20mm excess for each clamping dimension is recommended. Volume of substrate is an input data in WAAM cost model. The calculation equation for cost of substrate material is shown as below:

$$\boldsymbol{C_{sm} = V_{sm} \times \rho_{sm} \times C_{sub}} \quad \textbf{(5-2)}$$

Where

C_{sm} = substrate material cost

V_{sm} = volume of substrate material

$\boldsymbol{\rho}_{sm}$ = Density of substrate material

C_{sub} = substrate material sheet metal cost

- **WAAM material cost**

The total WAAM material cost can calculate by below equation:

$$\boldsymbol{C_m = C_{dm} + C_{sm}} \quad \textbf{(5-3)}$$

Where:

C_m = Material cost

C_{dm} = Deposition material cost

C_{sm} = Substrate material cost

5.2.2 Deposition cost

In deposition cost calculation, an important cost is welding cost. Near-net shape part is formed in welding process. Process planning parameters and volume of deposited material are the major factors which can influence welding cost.

On the basis of process planning, besides deposition cost, there are two special characteristics in deposition process, Shielding gas cost and wire change cost, which should be considered in deposition cost calculation.

Because the principle of WAAM cost model is to make a connection between time distributions and machine & labor hourly rate to estimate manufacture cost. Therefore, the first step is the calculation of welding machine hourly rate and labour hourly rate.

5.2.2.1Welding machine hour rate

The cost of equipment is obtained from a quotation supplied by one of dealers. The total machine cost includes a 6-axis robot and the integrated CMT welding machine and necessary accessories and the welding machine cost is £92,000. Machine depreciation time is 5 year and machine utilization rate is the maximum 60%[28]. Based on the straight line depreciation method the calculation formula is shown as follows:

$$\boldsymbol{R_m = \frac{C_{machine}}{t_u \times R_u}} \tag{5-4}$$

Where:

R_m = Machine hourly rate

$C_{machine}$ = Machine cost

t_u = Machine utility time

= No.of Year × No.of Week × Working Days per Week × Working Hours per Day

R_u = Machine utilization rate

5.2.2.2 Operator Hour Rate

The operator hourly rate is advised by a major aerospace company in UK. Operator hour rate (R_O) is 100 £ /Hour. The author thought it was too high and maybe including overhead cost and overhead cost is not includes in the WAAM cost model, so, the data is used in WAAM and CNC machining cost model. Operator hourly rate is change with the time and environment. Operator hourly rate can be changed by users in WAAM and CNC machining cot model.

5.2.2.3 Welding cost

The welding cost is determined by welding time and welding time is determined by volume of deposited materials and wire feed speed. The calculation equation adapted from [30]is shown as follows:

- Deposition rate (R_d)

$$\boldsymbol{R_d} = \frac{1}{4} \times (\boldsymbol{\pi} \times \boldsymbol{D_w^2} \times \boldsymbol{WFS} \times \boldsymbol{\rho_m}) \tag{5-5}$$

Where:

D_w = Diameter of filler wire

WFS = wire feed speed

$\boldsymbol{\rho}_m$ = Density of material

- Time of Welding (t_w)

$$\boldsymbol{t_w} = \frac{\boldsymbol{V_{dep}} \times \boldsymbol{\rho_m}}{\boldsymbol{R_d} \times \boldsymbol{E_p}} \tag{5-6}$$

$$= \frac{4 \times \boldsymbol{V_{dep}}}{\boldsymbol{\pi} \times \boldsymbol{D_w}^2 \times \boldsymbol{WFS} \times \boldsymbol{E_p}}$$

From the equation we can see that deposition time is determined by diameter of wire and wire feed speed.

- Welding cost (C_d)

$$\boldsymbol{C_w} = \boldsymbol{t_w} \times (\boldsymbol{R_m} + \boldsymbol{R_O}) \tag{5-7}$$

Where:

C_w = Welding cost

t_w = Time of welding

R_m = Machine hourly rate

R_o = Operator hourly Rate

5.2.2.4 Shielding gas cost

Shielding gas is a special characteristic of WAAM and it is very necessary to keep a stable welding operation and protect the weldment from atmosphere contamination. Shielding gas cost is determined by deposition time and comprise types of shielding gas, the cost calculation equation show as below, this equation is adapted from[30]:

Shielding gas cost **(C_g):**

$$\boldsymbol{C_g = \frac{R_g \times C_{gc}}{V_g} \times t_d} \tag{5-8}$$

Where:

C_g = Shielding gas cost

R_g = Gas flow rate

C_{gc} = Gas cost per cylinder

V_{gc} = Volume of cylinder

t_d = Deposition time

5.2.2.5 Wire Change Cost

Every time, wire needs to be changed because of using out. Two costs are incurs: one is machine idle time, while an operator replace old wires and install a new roll, the cost of machine idle time will produce. The other one is new wires cost and the cost of new wires has been included in material cost. The wire change time per once is depending on the experiences of operators. On the basis of expert's experiences in WELPC, the wire change time per once is 300 seconds. Therefore, the time for wire change cost can be calculated by equations shown as follows:

Wire change time (t_c)

$$\boldsymbol{t_c} = \frac{V_{dep} \times \rho_m}{M_w} \times \boldsymbol{N_c} \tag{5-9}$$

Wire change cost (C_c)

$$\boldsymbol{C_c} = \boldsymbol{t_c} \times (\boldsymbol{R_m} + \boldsymbol{R_O}) \tag{5-10}$$

Where:

t_c= Wire change time

M_w = Mass of filler wire per roll

C_c = Wire change cost

V_{dep} = Volume of deposition

$\boldsymbol{\rho}_m$ = Density of material

N_c = Number of deposition time

R_m = Machine hourly rate

R_o = Operator hourly Rate

5.2.2.6 Deposition cost

The total deposition cost is obtained by summing up the individual cost together, the equation show as below:

$$\boldsymbol{C_d} = \boldsymbol{C_w} + \boldsymbol{C_g} + \boldsymbol{C_c} \tag{5-11}$$

Where:

Cd = Cost of deposition

Cw = Cost of welding

Cg = Cost of shielding gas

Cc= Cost of wire change

5.2.3 Finish-machining cost

For the purpose of ensuring the required accuracy of surfaces and dimensions, finish-machining is usually arranged follow welding and milling or Grinding is the popular used methods. In WAAM cost model, finish-machining choose CNC machining, therefore, finish-machining manufacture cost can be estimated by CNC cost model which developed in previous. It should be noticed that there is no material cost in this process which has been involved in WAAM material cost.

5.2.3.1 Finish-machining cost

The finish-machining time can be calculated by the surface generation speed of machine which has the same procedure as introduced in chapter 3. Equation (3-3) and (3-5) in chapter 3 applied to estimate CNC machining cost. The machining parameters can obtained from the Machining Data Handbook[31].

In WAAM finish-machining cost estimation model, the calculation process has the same default values as CNC machining cost model, that means, same type of CNC equipment is used in WAAM finish-machining and CNC machining.

5.2.4 Set-up cost

Two machines are used in independent WAAM manufacture process. One is welding equipment, the other is CNC machine. The set-up time for CNC machine can be obtained from Boothroyd's book[7] or machinery hand book and set-up activities are also discussed in this book[31]. In WAAM deposition process, set-up activities include transforming the program into the robot, simulate and test program, set-up machine. After discussed with experts in welding centre and personal observation, currently, set-up time for deposition process is 1.5 hours per one deposition operation. however in practice, when parts need to be turned-over or re-located in deposition process and all set-up work needs to be repeated again, therefore, the term number of deposition is used to calculate the set-up time in WAAM cost model.

In Boothroyd's book, for CNC machining, machine set-up time is 1.5 hour[7]. If integrated WAAM manufacture method is selected and deposition and finish-machining can be arranged in one machine. Then, the set-up time for finish-machining machine is 0.

The set-up cost of WAAM equation is shown as below:

Set-up time (t_s)

$$\boldsymbol{t_s = T_{sd} \times N_d + t_{sf}} \quad \textbf{(5-12)}$$

Set-up cost (C_s):

$$\boldsymbol{C_s = t_s \times (R_m + R_O)} \quad \textbf{(5-13)}$$

Where :

t_{sd} = Deposition machine setup time

t_{sf} = Finish-machining machine setup time

N_d = Number of depositions

t_s = setup time

R_m = Machine hourly rate

R_o = Operator hourly Rate

5.2.5 Non-productive cost

I In WAAM, two kinds of non-productive time need to be considered in WAAM cost models. One incurs in deposition process and the other one incurs in finish-machining process. In deposition, non-productive time incurs every feed and speed setting changed; the torch engagement and disengagement, in WAAM most of non-productive time is waiting and cooling time, therefore, the non-productive time is relate to the part geometry. In WAAM cost model, the non-productive time is relate to welding time and the term build time efficiency is used to represent the time utilization in welding process and 95% build time efficiency is suggested by an expert in WELPC. In finish-machining, the equipment is CNC machine, the non-productive time can be obtained from Boothroyd's book[7], for each operation, non-productive is 83 seconds. The term number of finish-machining operations is used to calculate the total non-productive time in finish-machining and it is relate to every tool change and turn-over in manufacture process. The non-productive cost calculation equation in WAAM cost model is shown as below:

Non-productive time (t_n)

$$\boldsymbol{t_n = (t_w \times (1 - E_t) + (t_{nf} \times N_s)} \quad \textbf{(5-14)}$$

Non-productive cost (C_n)

$$\boldsymbol{C_n = t_n \times (R_m + R_o)} \quad \textbf{(5-15)}$$

Where:

E_t = Build time efficiency

t_{nf} = finish-machining non-productive time

N_s = Number of finish-machining operations

t_n = Non-productive time

t_w = Time of welding

R_m = Machine hourly rate

R_o = Operator hourly Rate

5.2.6 WAAM cost

The total manufacture cost of WAAM is acquired by summing up the individual costs:

WAAM cost (C_{waam})

$$\boldsymbol{C_{waam} = C_m + C_d + C_s + C_n} \quad \textbf{(5-16)}$$

Where:

C_{waam} = WAAM cost

C_m = Material cost

C_d = Deposition cost

C_s = Setup cost

C_n = Non-productive cost

5.3 Expert feedback on cost model

The discussion of this research is carried out by experts in WELPC at Cranfield University. Two experts in WELPC were invited to join the meeting. One is an expert in WAAM research and operation and the other one is a senior of WELPC who has many experiences in WAAM process planning and operations. All the research works have been demonstrated in the meeting and the calculation process and results have been discussed too. The developed the process planning for WAAM also discussed in the meeting.

On the basis of the meeting, a cost model for WAAM is essential because more and more customers are interested in WAAM and they like to know the manufacture cost of WAAM. At the same time, more and more people like to compare WAAM with traditional manufacture and they need a direct understanding about the costs of two kinds of methods and determine which one is more time efficiency and which one is more economic. They also suggested that a cost model must be simple enough for user to enter inputs data and the calculation process must be traceable and maintainable. This can help users to understand the cost model and make necessary changes with practical applications. The cost model should be easily used by anyone who even do not know too much details about WAAM. So it is necessary to set some default values in cost model. Some of recommendations are also made after the meeting

Some of recommendations are also made after the meeting

- The titanium sheet metal cost should be £60/kg not £20/kg.

- For CNC rough-machining, it should be quoted as volume.
- Make all the calculation visible to the user so that they can follow calculation process.
- Make sure that WAAM and CNC cost are consistent for finish-machining.
- It is suggested that add "part build efficiency" as a input for user and assume part build efficiency is 80% as a default value.
- Non-productive time is difficult to estimate because it depends on the part geometry, 5% welding is recommended as default value.
- It is recommended that add an option to the spreadsheet to calculate the cost for an integrated WAAM/CNC machine.

All the recommendations have been verified and re-corrected in WAAM and CNC machining cost models. This makes the cost model more reasonable and functional.

5.4 Chapter summary

In this chapter a cost estimation model for WAAM has been developed and all research works has been reviewed by experts in WELPC at Cranfield University. The improvements for the cost model have been re-corrected after the meeting. Two cost models have been built, one for CNC and one for WAAM, therefore, the next work is to find a way to combine two cost models together and realize the aim of compare two manufacture costs at the same time.

6 A developed cost calculation spreadsheet

The cost estimation model for WAAM and CNC machining has been developed respectively. A new requirement emerged after the meeting. Sometimes, managers or customers not only need to know results of cost estimation but also need to know the details including time distributions and cost distributions. This can give them a directly idea that which manufacture method is more efficient and what is advantages and disadvantages of two methods on time and cost. So the next step of this research is to find a way to integrate WAAM and CNC machining cost model.

6.1 The thinking process of spreadsheet development

At first, on the basis of two cost models, two spreadsheets have been built to calculate manufacture cost respectively. It is easy to develop different spreadsheets since each cost model uses different default value, input and output data etc. However the test results shows that some new problems emerged, firstly, there are too much input and output in cost model; Secondly, it is difficult to compare the calculation results of two cost models; Thirdly, in order to make the calculation simple and clear, it is necessary to show time consumes and cost contributions in cost calculation process.

In order to solve above problems, many tests have been done. The first work is analyse WAAM manufacture process makes it more reasonable in accordance with the user' requirements. The Second work is to integrate two cost models in one spreadsheet. Initially, two cost model co-exist in one excel sheet and there are no connection between two cost models. A user has to input the same information twice for one calculation. Therefore, more improvements been done to find the connections between two cost models for the aim of sharing common information and convenient comparison. Thirdly solve the data source problems, in the beginning, all the calculation and calculation process have been hide behind the spreadsheet and the spreadsheet only show the calculate results. It is difficult to let the user understand the spreadsheet and calculate process. It is difficult for a user understand the calculation process and it is nearly impossible to change some default values according to the practical status. Many improvements have been done to show all the calculation process and to make it simple and more flexible.

Finally, a simple, easy to use and clear cost calculation spreadsheet has developed and it integrates WAAM and CNC cost estimation models together and can show the time distributions and cost distribution for every manufacture process automatically.

6.2 Calculation spreadsheet introduction

A cost calculation spreadsheet has been developed and an introduction to the cost calculation spreadsheet is through calculation process to show the input and output of two cost models.

6.2.1 WAAM cost calculation spreadsheet

Figure 6-1 shows the title of spreadsheet and the function introduction to spreadsheet. There are three kinds of input data in cost model, the blue column is input data, the yellow column is the option data which a user can choose from drop down list, and “reset” button is to attach default value to cost spreadsheet.

	A	B	C	D	E	F	G
1	WAAM and CNC Machining Cost Estimation and Comparison						
2	Product Information input		unit				
3	Volume of Part	1408000	mm^3		Spreadsheet Instructions		Input Data
4	Surface Area of Part	292000	mm^2				Select Option from List
5	Batch Size	1				Reset	Default Value
6	WAAM Manufacture Cost Estimation		Reset		CNC Manufacture Cost Estimation		
7	Manufacture Method	Independent WAAM			Manufacture Method	CNC	UNIT
8	Material Data				Material Data		
9	Material Type	Titanium			Material Type	Titanium	
10	Wire Diameter	1.2	mm		Density	4428.00	kg/m^3
11	Material Density	4428.00	kg/m^3		Thickness	Thickness<12.7mm	mm
12	Wire Metal Cost	150	£/kg		Sheet Metal Cost	60.00	£/kg
13	Substrate Thickness	Thickness<12.7mm	mm		Equipment Data		

Figure 6-1 Title of cost calculation spreadsheet

As shown in Figure 6-1, the shared information for two manufacture methods are the volume of parts, surface area of parts and batch size. All the information can be obtained from the design information. After the user input the shared data, then the cost calculation enter into each manufacture method.

The default value of WAAM cost calculation spreadsheet show in Figure 6-2

	A	B	C
6	WAAM manufacute cost estimation		Reset
7	Manufacutre Method	WAAM and CNC	
8	Material Data		
9	Material Type	Titanium	
10	Wire Diameter	1.2	mm
11	Material Density	4428.00	kg/m³
12	Wire Metal Cost	150	£/kg
13	Substrate Thinckness	Thickness<12.7mm	mm
14	Substrate Metal Cost	60.00	£/kg
15	WAAM Data		
16	Machine Cost	92000	
17	Machine hour Rate	16.43	£/hr
18	Operator houreRate	100	£/hr
19	Consumable cost	2.7	£/hr
20	Set-up Time	1.5	h
21	Nonproductive Time	1411.17	s
22	Finish-machining Data		
23	Equipment	CNC	
24	Cutter Material	Brazed Carbide	
25	Taylor Tool-life Index	0.25	
26	Cutting speed	79	m/min
27	Feed per tooth	0.15	mm
28	Surface Generation Rate	0.012	m²/min
29	Machine Cost	64260	
30	Machine hour Rate	10.04	£/h
31	Operator houre Rate	100	£/h
32	Set-up Time	1.5	h
33	Nonproductive Time	85	s

Figure 6-2 Default values for WAAM in cost calculation spreadsheet

The following introduction follows the spreadsheet orders. In WAAM cost estimating, the first section of calculation is to choose WAAM manufacture methods, independent WAAM or Integrated WAAM, this would affect the results of cost calculation. The second section is material data selection. The user can choose material and substrate thickness from drop down list, and in this way, the material density and material cost will show automatically. The third section is WAAM data selection, some default values have been shown in the column and the user can change any information according to practical status and other data is about the WAAM process arrangement. The fourth section is finish-machining data and the default equipment is CNC machine. Then the option data is cutter material which will influence the surface generation rate. All the default values are about machine and manufacture process and also can be changed by the user.

	A	B	C
34	Input		
35	Volume of Deposition	608000	mm^3
36	Volume of Substrate	924000.00	mm^3
37	Part Build Efficiency	0.80	%
38	Wire Feed Speed	3.00	m/min
39	Number of deposition operations	1	
40	Number of Finish-machining operations	2	
41	Build time efficiency	0.9	%
42	Calculation process		
43	Deposition rate	0.90	kg/hr
44	Time for welding	3.92	h
45	Time for finish-machining	1661.21	s
46	Corrected finish-machining time	2214.95	s
47	Substrate material cost	245.49	£
48	Welding material cost	504.79	£
49	Results		
50	Time for manufacture	4.97	h
51	Material cost	750.28	£
52	Set -up cost	508.81	£
53	Nonproductive cost	51.89	£
54	Welding cost	466.98	£
55	Finish-machining cost	67.70	£
56	Manufacture cost	534.68	£
57	Shielding Gas cost	0.1349	£
58	Wire change cost	3.82	£
59	WAAM cost	1849.62	£

Figure 6-3 Input and output for WAAM in cost calculation spreadsheet

The input and output of WAAM cost calculation spreadsheet are shown in Figure 6-3. Input manufacture process data is the fifth section. These data can acquire from process planning arrangements and quality requirements. Part build efficiency is applied to calculate the volume of actual deposited materials and can be seen as the target of deposition. Wire feed speed is determined by the thickness of parts and a planner can choose optimum wire feed speed on the basis of different thickness of parts. Deposition operation numbers is determined by the process planning arrangements and default value is 1. Considering a change of tools and turn-over arrangements in process planning, finish-machining operation numbers is used to change the non-productive time and default value is 2 because all the surface of a part need finish-machining and the part must be turn-over at least once. The sixth section of spreadsheet is calculation process and involves all interchange data and the calculation process. The final section of spreadsheet shows the results of cost estimation and all the time distributions and cost distributions are shown in Figure 6-3.

The more details of spreadsheet are show in Appendix A.

6.2.2 CNC cost estimation spreadsheet

The data shared by two cost models has introduced in chapter 6.2.1and details of CNC machining cost estimation spreadsheet is shown as **Figure 6-4**. The first section spreadsheet is also material data and the spreadsheet is designed for the same part, therefore, the material data in CNC machining changes with the selection in WAAM cost model. The user also can choose the thickness of billet from drop down list. The second section the data of equipment and Cutter and the default data is attach for calculation which can be changed by the user . Volume of billet and number of operations are the only input in CNC cost model and the detail has introduced in precious chapter. The calculation process is divided into rough-machining and finish-machining. The final section of the spreadsheet is calculation results and all the time distributions and cost distributions are shown in the column automatically.

	D	E	F	G
6		CNC Manufacture Cost Estimation		
7		Manufacture Method	CNC	UNIT
8		Material Data		
9		Material Type	Titanium	
10		Density	4428.00	kg/m^3
11		Thickness	Thickness<12.7mm	mm
12		Sheet Metal Cost	60.00	£/kg
13		Equipment Data		
14		Machine Cost	64260	£
15		Machine hourly Rate	13.39	£/hr
16		Operator hourly Rate	100	£/hr
17		Set-up Time	1.5	h
18		Non-productive Time	85	s
19		Available Power	5.215	kw
20		Cutter Data		
21		Cutter Material	Brazed Carbide	
22		Taylor Tool-life Index	0.25	
23		Cutting Speed	79	m/min
24		Feed per Tooth	0.15	mm
25		Surface Generation Rate	0.012	m^2/min
26		Specific Cutting Energy	0.05	$kw/cm^3/min$
27		Input		
28		Volume of Billet	6468000	mm^3
29		Number of Operations	8	Times
30		Calculation process		
31		Buy-to-Fly Ratio	4.59	
32		Time for Rough Machining(Volume)	0.81	h
33		Time for Rough Machining(Surface)	0.41	h
34		Time for Finish Machining(Surface)	0.46	h
35		Corrected Rough Machining Time (Including tool replacement cost)	1.36	h
36		Corrected Finish-machining Time (Including tool replacement cost)	0.62	h
37		Results		
38		Time for Manufacture	1.97	h
39		Material Cost	1718.42	£
40		Set-up Cost	170.08	£
41		Non-productive Cost	21.42	£
42		Manufacture Cost	223.53	£
43		Total CNC Cost	2133.45	£

Figure 6-4 Cost estimation process for CNC in cost calculation spreadsheet

6.3 Chapter summary

A cost calculation excel sheet has been developed and it can calculate the cost of WAAM and CNC machining at the same time or calculate each cost of them respectively. The satisfactory results of the validation demonstrate that the cost models and spreadsheet can realize the aims: estimating WAAM manufacture costs and CNC machining costs together, comparing two estimated costs at the same time. All the cost distributions in manufacture process have been shown in calculation results including manufacture time consume and cost distributions. Some calculation process are also shown in spreadsheet and can help the user to understand calculation process and compare required cost drivers as needed. The spreadsheet is simple and clear to allow the user to understand calculation process and the connections between each procedure and leave more space to optimum this method later.

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7 Case studies

Two parts have been chosen to demonstrate how to use the spreadsheet and investigate the cost drivers of WAAM and CNC machining. The cost compare of WAAM and CNC are also been made.

7.1 Case study 1: simple geometrical structure

The geometry selected for case study 1 is a simplified stiffener representative of a typical aerospace component which can be manufacture by CNC machining and WAAM. The part is used to test the capability of spreadsheet and investigate cost drivers of WAAM. Titanium alloy TI 6AL 4V is the material of part which is commonly used in aircraft manufacture industries. Batch size is assumed to be 1. The details of the component are shown in **Figure 7-1** and **Figure7-2**.

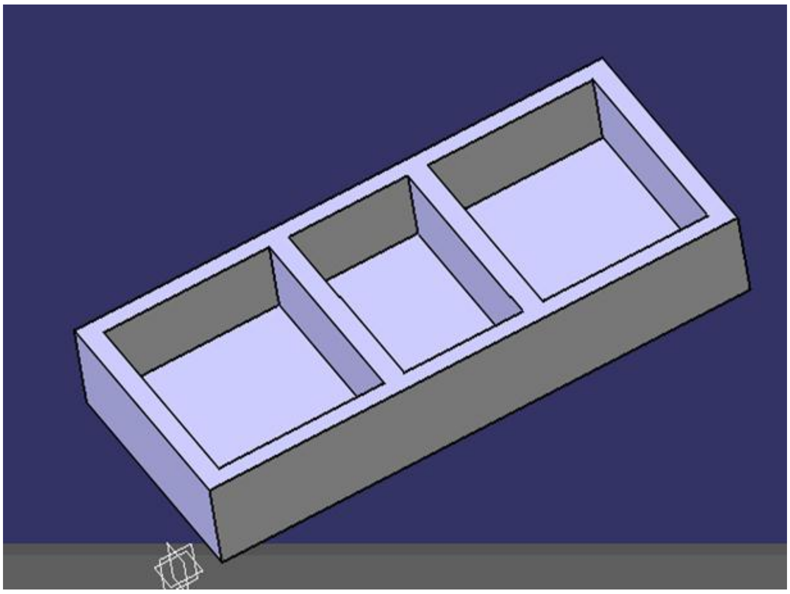


Figure 7-1 3D model of case 1 part

Figure7-2 2D dimension of case 1 part, the height of the part is 50mm,

Unit: mm

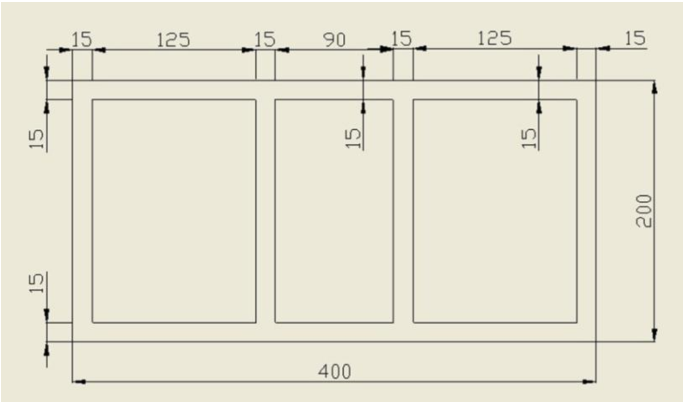


Figure7-2 2D geometry of case 1 part

7.1.1 WAAM cost analysis

There are two WAAM methods available to manufacture Case 1 part. One is integrated WAAM and the other one is independent WAAM. The process planning flow chart for two methods are shown in Figure 7-4 and

Figure 7-3

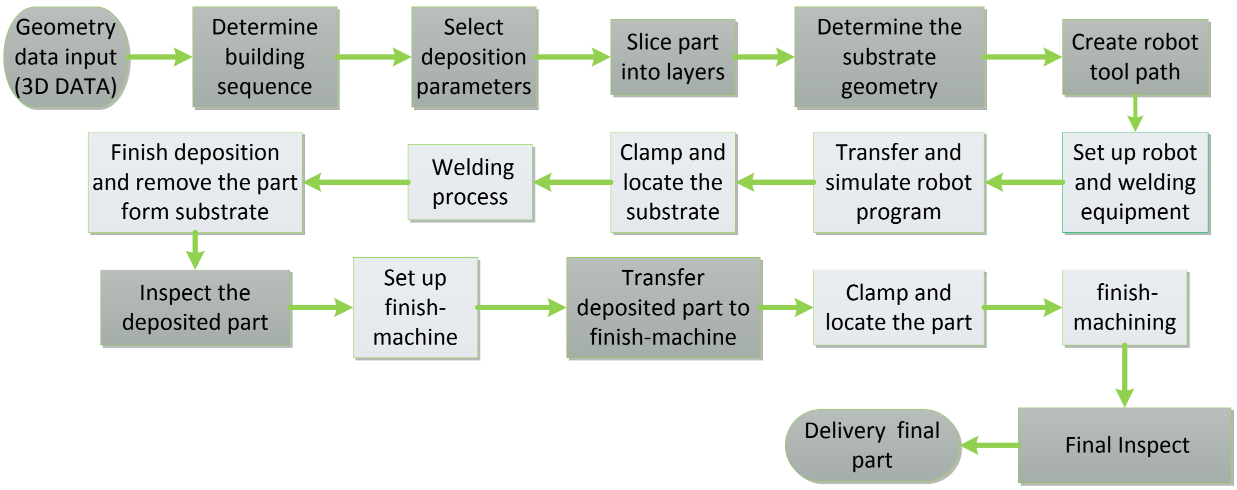


Figure 7-3 Process planning for case 1 part (independent WAAM)

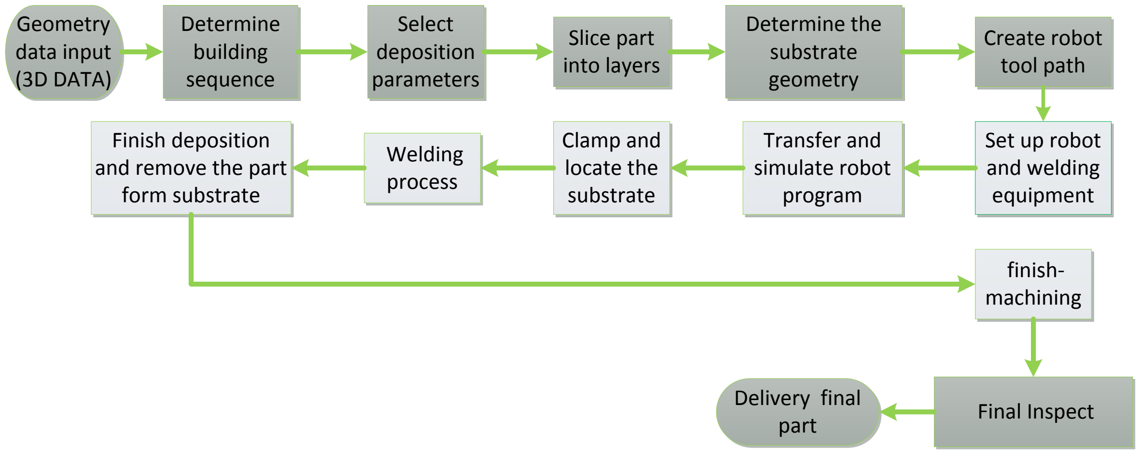


Figure 7-4 Process planning for case 1 part (integrated WAAM)

Analyse case 1 part, the bottom of the part can select as substrate. Therefore, two kinds of substrate are selected to manufacture case 1 part and 20mm excess in clamping directions and 5mm excess in thickness direction for substrate should be added when calculate the volume of substrate.

Generally, part build efficiency for titanium is 80%, for case 1 part, number of deposition operations is 1, number of operation for finish-machining is 2.

The default value of WAAM cost estimation is shown in **Table 7-1**, the input and output of the calculation also is shown in **Table 7-2**.

Default Values for WAAM Cost Estimation (case 1 part)			
Items	Name	Data	Unit
Filler Wire	Filler Wire Diameter	1.2	mm
	Density of Filler Wire	4428	kg/m^3
	Filler Wire Metal Cost	150	£/kg
	Mass of Wire per Roll	7	kg/roll
Machine and Operator	Welding Machine Cost	92,000	£
	Operator hour Rate	100	£/h
Shielding Gas Parameters	Gas flow Rate	3700	mm^3/min
	Gas Cost per Cylinder	154.98	£
	Volume of Cylinder	10	m3
Substrate	Density of Substrate Material	4428	kg/mm^3
	Metal cost of Substrate Material	60	£/kg
Time Contributions	Set-up Time	1.5	h
	Non-productive Time	83	s
	Wire Change Time	300	s
	Part Build Efficiency	0.8	%
	Build Time Efficiency	0.95	%

Table 7-1 Default value in WAAM cost estimation for case 1 part

Input and Output of WAAM Cost Estimation (case 1 part)			
Items	Name	data	unit
Input	Volume of Part	1408000	mm^3
	Surface Area of Part	292000	mm^3
	Volume of Deposition	608000	mm^3
	Volume of Substrate	924000	mm^3
	Wire Feed Speed	3	m/min
	Batch Size	1	
	Deposition Operation Times	1	
	Finish-machining Operation Times	2	
Output	Time for manufacture	4.55	h
	Material cost	750.28	£
	Set-up cost	524.48	£
	Non-productive cost	28.29	£
	Welding cost	458.73	£
	Finish-machining cost	69.76	£
	Manufacture cost	528.49	£
	Shielding Gas cost	0.13	£
	Wire change cost	3.94	£
	Total WAAM cost	1835.60	£

Table 7-2 Input and output in WAAM cost estimation for case 1 part

7.1.2 CNC cost estimation

For CNC machining, the input for CNC model are volume of billet and operation numbers. Volume of billet can be calculated by necessary excess plus maximum size of part in each dimension. 15mm excess is to be added in clamping direction and 5mm excess is to be added in thickness direction. The buy-to fly ratio for this part is 4.59. Number of operation is determined by the geometry of the part, since the part need to turn-over 6 times in initial surface manufacture and 2times tool change for rough machining and finish-machining, hence, the number of operation for manufacture is 8.

The default value for CNC cost estimation is shown in **Table 7-3**, the input and output data is shown in Table 7-4.

Default Values for CNC Cost Estimation (Case 1 part)			
Items	Name	Data	Unit
Material	Titanium	60	£/kg
	Steel	15	£/kg
	Aluminium	20	£/kg
Machine and Operator	CNC Machine Cost	64,200	£
	Operator hour Rate	100	£/h
Manufacture Parameters	Specific Cutting Energy	0.05	kw/cm^3/min
	Cutter Material	Brazed carbide	
	Cutting Speed	79	m/min
	Feed per Tooth	0.15	mm
Time Contributions	Available Power	5.215	kw
	Taylor Tool-life Index	0.25	
	Set-up Time	1.5	h
	Non-productive Time	85	s

Table 7-3 Default value in CNC cost estimation for case 1 part

Input and Output of CNC cost estimation (Case 1 part)			
Items	Name	Data	Unit
Input	Volume of billet	6468000	mm^3
	Operation number	8	
Output	Time for manufacture	1.97	h
	Material cost	1718.42	£
	Set-up cost	170.08	£
	Nonproductive cost	21.42	£
	Manufacture cost	223.53	£
	Total CNC cost	2133.45	£

Table 7-4 Input and output in CNC cost estimation for case 1 part

Compared with CNC machining, WAAM technology shows massive reduction in material cost and manufacture cost. For case 1 part, assuming the batch size is 1, the manufacture cost can only reduce 14% compared with WAAM. the buy-to-fly ratio for this part is only 4.59 which is relatively low for aerospace components of this type.

Case study 1 has demonstrated how to use cost spreadsheet and test developed cost model. The result shows that developed models and calculation spreadsheet can met the function requirements and fulfil the research aim. This calculation spreadsheet can be easily extended for any geometry parts because its only use limited design and process planning data and can automatically calculation manufacture cost of WAAM and CNC in seconds.

7.2 Case study 2: a practical aerospace part

Case study 2 selected a practical aerospace part which is shown in Figure 7-5, the name is pylon bottom beam, part material is TI6-AL-4V. The part is provided by an aerospace company and it is manufactured by CNC machining and lots of materials are wasted. The volume of the material is 2947000mm^3 and the surface of the part is 1365000mm^3. For WAAM manufacture, analysing the geometry of the part, selecting partial substrate, therefore volume of deposition is 867470 mm^3. 20mm excess is added to each dimensions of the substrate, hence volume of substrate is 4134147mm^3. For CNC machining, 15mm excess is added to the maximum size of the part, so the billet of the part is 43581997mm^3, and the buy-to-fly ratio for this part nearly is 14.8.

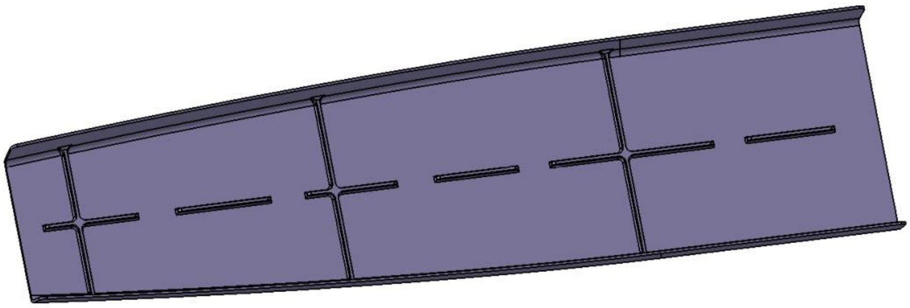


Figure 7-5 Case study 2: pylon bottom beam

The input and output of the cost model for WAAM and CNC show in **Table 7-5** and **Table 7-6** respectively:

Input and Output of WAAM Cost Estimation (Case 2 part)			
Items	Name	data	unit
Input	Volume of Part	2947000	mm^3
	Surface Area of Part	1365000	mm^3
	Volume of Deposition	867470	mm^3
	Volume of Substrate	4234147	mm^3
	Wire Feed Speed	3	m/min
	Batch Size	1	
	Deposition Operation Times	1	
	Finish-machining Operation Times	2	
Output	Time for manufacture	8.48	h
	Material cost	1845.15	£
	Set-up cost	524.48	£
	Non-productive cost	38.08	£
	Welding cost	654.49	£
	Finish-machining cost	326.12	£
	Manufacture cost	980.61	£
	Shielding Gas cost	0.18	£
	Wire change cost	5.62	£
	Total WAAM cost	3394.11	£

Table 7-5 Input and output in WAAM cost estimation for case 2 part

Input and Output of CNC cost estimation (Case 2 part)			
Items	Name	Data	Unit
Input	Volume of billet	43581997	mm^3
	Operation number	8	
Output	Time for manufacture	11.93	h
	Material cost	11578.86	£
	Set-up cost	170.08	£
	Nonproductive cost	21.42	£
	Manufacture cost	1352.62	£
	Total CNC cost	13122.99	£

Table 7-6 Input and output in CNC cost estimation for case 2 part

The figure illustrates that WAAM can dramatically reduce material cost and manufacture time for case 2 part. If do not consider the material recycle cost, WAAM can reduce almost 85% material for this part and can reduce 30% manufacture time and manufacture cost by 75%.

8 Results and discussions

The day-to-day challenges of manufacturing in a competitive environment forces company quickly response to requirements from supplier or customer. For the purpose of providing necessary cost information to supplier or customer in short time. It is necessary to develop a cost model for WAAM. In this research, a cost model for WAAM and CNC machining has been developed respectively and a cost estimation spreadsheet has been developed. The models and spreadsheet have been validated by the experts in WELPC at Cranfield University. On the basis of two case studies, it has been proved that two cost models and excel calculation spreadsheet are very useful in estimating a product cost in early design stage. By integrating two cost models together, the developed spreadsheet addresses a gap in current cost estimating methods and provides a robust method for evaluating manufacture cost of WAAM and CNC machining.

This chapter is devoted to show the results of the research and analyse the cost results which based discussed in chapter 7. The influence of different manufacture methods, different material and different process parameters will be discussed. Then, the cost drivers of WAAM is to be identified and the improvements in cost reduction are also been discussed.

All the data used in calculations are present in Appendix B.

8.1 WAAM cost drivers analysis

This section is dedicated to discuss the cost drivers which obtained from developed WAAM cost estimation model. All the analysis is based on case 1 part. The comparison is carried out to investigate the cost drivers in WAAM and find efficient ways to reduce manufacture cost of WAAM.

8.1.1 WAAM cost breakdown

There are many costs involves in WAAM manufacture process. Figure 8-1 shows the cost breakdown of WAAM including independent WAAM method and integrated WAAM method.

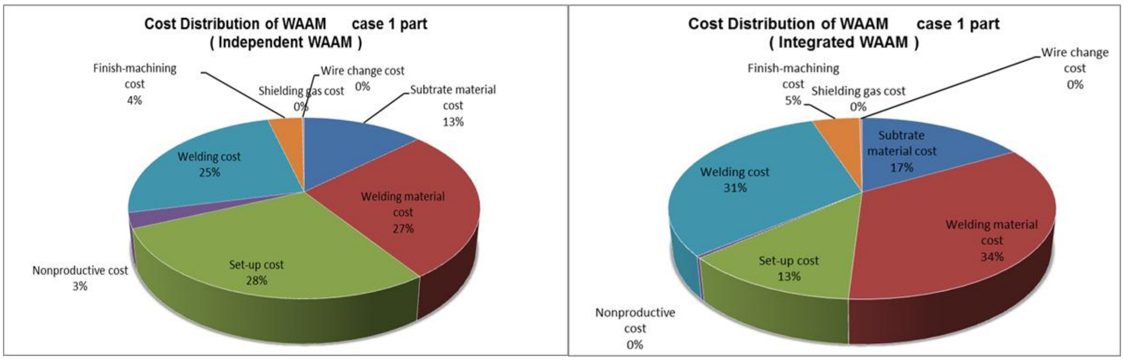
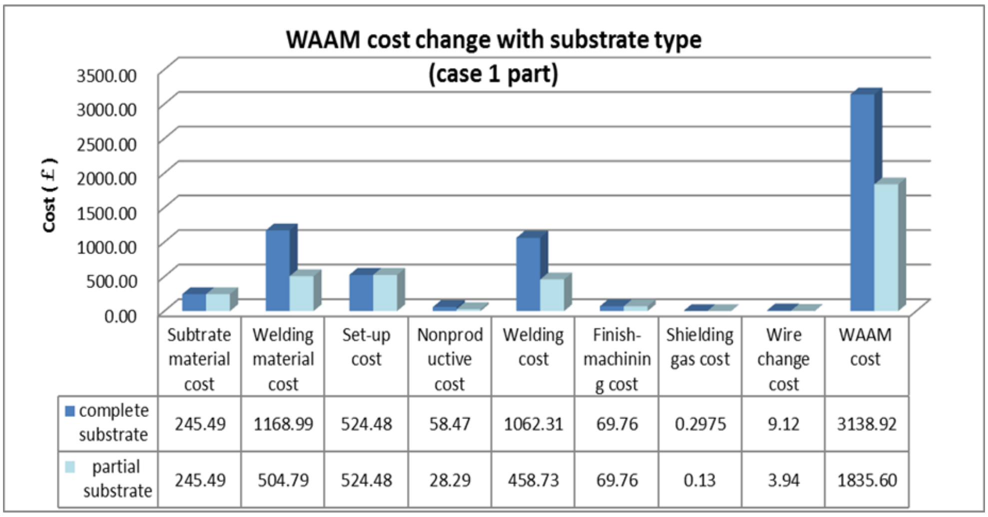


Figure 8-1 Two WAAM manufacture methods cost breakdown (case 1 part)

The figures illustrate that there are some common results for two different WAAM manufacture methods. The shielding gas cost and wire change cost are very small compared with other cost drive which is less than 1% and it may increase with the volume of deposited materials. Material cost still is the major cost contributions in WAAM cost and substrate material cost and welding material cost occupied almost 50% of total manufacture cost. The only difference in two methods is the set-up cost, in independent WAAM method, there are two machines used in manufacture process and the set-up time almost reach 28% cost and it is even larger than welding cost (25%). In integrated WAAM method, the set-up cost is dramatically reduced to 13%. Therefore, integrated WAAM method is strongly recommended.

8.1.2 Substrates

As discussed in previous, the substrate is divided into complete substrate and partial substrate. Based on experiences of experts, partial substrate is cheaper than complete substrate. From an economics point the influence of substrate for WAAM cost is discussed. Figure 8-2 shows WAAM cost change with substrate type.



	Subtrate material cost	Welding material cost	Set-up cost	Nonproductive cost	Welding cost	Finish-machining cost	Shielding gas cost	Wire change cost	WAAM cost
complete substrate	245.49	1168.99	524.48	58.47	1062.31	69.76	0.2975	9.12	3138.92
partial substrate	245.49	504.79	524.48	28.29	458.73	69.76	0.13	3.94	1835.60

Figure 8-2 WAAM cost change with substrate type (case 1 part)

The result illustrates an important phenomenon that the selection of substrate can dramatically influence the manufacture cost of WAAM. The figure shows that welding material cost and welding cost of complete substrate part are much higher than that of partial substrate part due to the welding material decrease. Therefore, it is suggested to designers that part of component act as substrate can reduce manufacture cost of WAAM when design the component. The same suggestion is also recommended to process planner that choosing partial substrate can reduce manufacture cost.

8.1.3 Material influence

At present, titanium, aluminium, steel are three kinds of materials are widely used in WAAM. In order to identify which material shows more advantages in WAAM. The cost comparisons of same part manufactured by three different materials have been carried out in independent WAAM condition. **Figure 8-3** shows manufacture cost comparison of three materials.

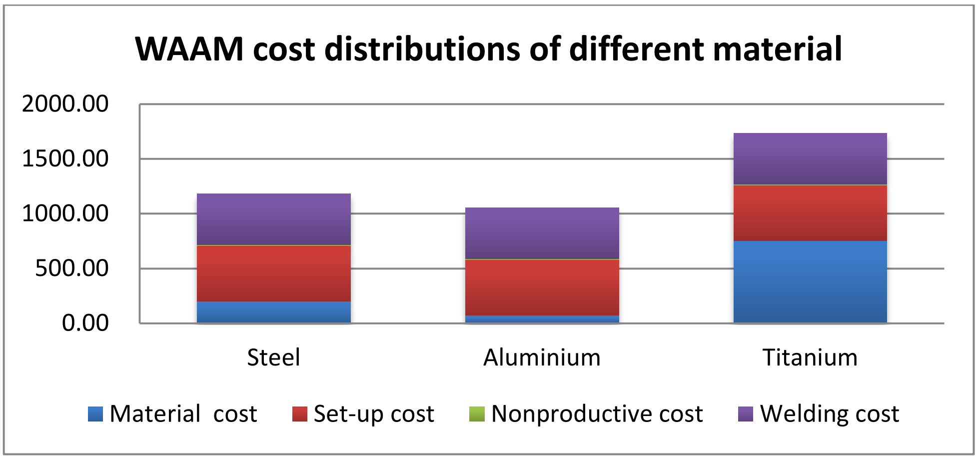


Figure 8-3 WAAM cost distributions of different material

From these Figures we can see that the major cost contributor of WAAM is different for different material. For Titanium, the major cost contribution is material, but for steel and aluminum, the major cost contribution is welding cost. The potential reason is the wire metal cost of titanium is much higher than steel and aluminum. Therefore, for titanium, reduce the wire metal cost is a good way to reduce WAAM cost. But for steel and aluminum, the reduction of welding cost is recommended to reduce WAAM cost.

8.1.4 Wire feed speed

As mentioned before, another way to reduce WAAM cost is the reduction of welding cost which is determined by the volume of deposited materials and wire feed speed. Volume of deposition is determined by the geometry of the part, therefore it is necessary to investigate the effect of wire feed speed on WAAM cost. WAAM cost change with wire feed speed is shown in Figure 8-4. Wire feed speed is a process planning parameter and it is decided by the thickness of parts and part build efficiency. With the higher wire feed speed the cost of WAAM can dramatically be reduced.

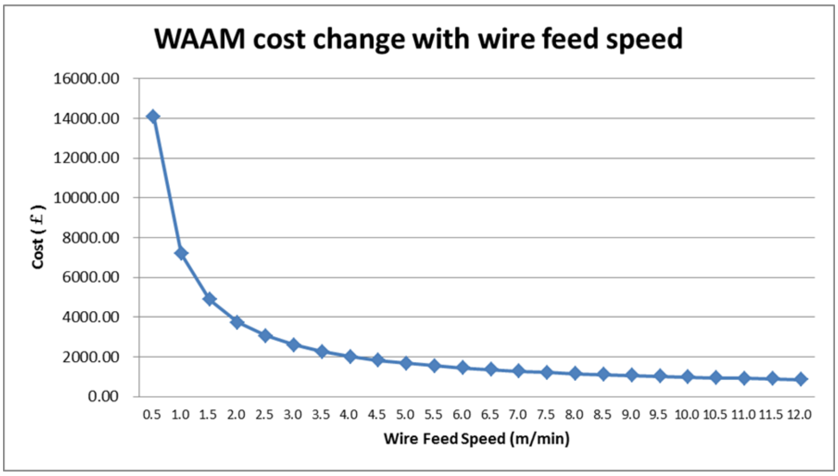


Figure 8-4 WAAM cost change with wire feed speed (case 1 part)

From the graphs is shown in Figure 8-4 we can conclude that by increase 50% wire feed speed it would produce almost 50% reduction in part manufacture cost. With the increase of wire feed speed, the reduction in part manufacture cost gradually tend to small. When the wire feed speed almost reach 6mm/min, the part manufacture cost tend to stabilize because the welding cost is very small compare with other cost. However it should be mentioned that the wire feed speed may not be increased unlimited as shown in figure 8-4. Actually, high wire feed speed induces poor quality of product at present technical.

8.1.5 Batch size

The curve relating the cost/part of batch size is shown in **Figure 8-5**.

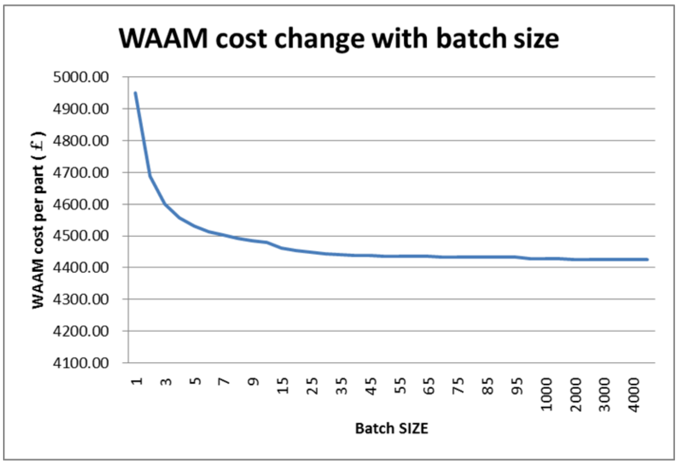


Figure 8-5 WAAM cost per part change with batch size

When the number of part reaches to 15 and the curve tends to stabilize. This happens because the set-up cost in cost model is split on the number of parts and the influence of set-up cost is tended to zero.

8.2 Cost compare of WAAM and CNC

For a comparative cost analysis of WAAM and CNC machining, it is proposed to use the same component which has been demonstrated in case study 1.

8.2.1 CNC cost breakdown

For the purpose of comparing the manufacture cost of WAAM and CNC, it is necessary to know the cost comparison of each method. WAAM cost breakdown has been demonstrated in chapter 8.1.1 and CNC cost breakdown is shown in **Figure 8-6**

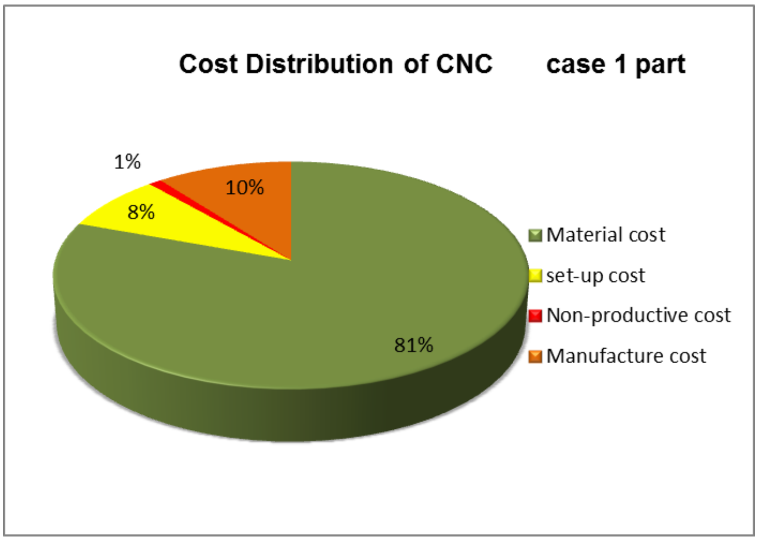
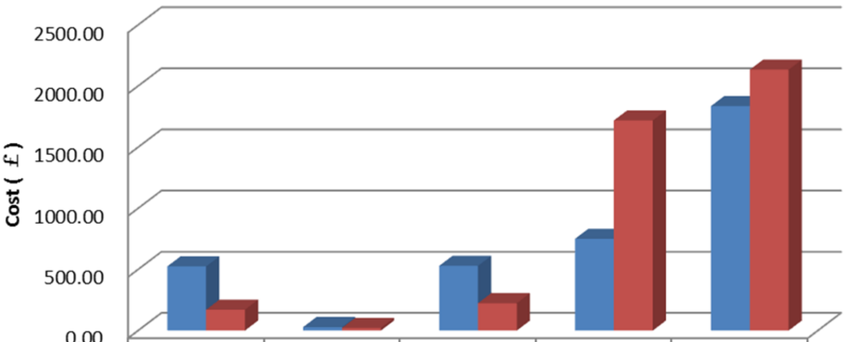


Figure 8-6 CNC machining cost breakdown (case 1 part)

For case 1 part, 81% cost contributions are material cost for CNC machining and for WAAM the material cost is only 50%. The manufacture cost of CNC machining is lower than WAAM and the potential reason is the high cutting speed in CNC machining.

8.2.2 Cost compare of WAAM and CNC

On the basis of developed cost model and excel spreadsheet, the cost contributions of WAAM and CNC can be compared at the same time. **Figure 8-7** shows the cost comparison of WAAM and CNC.



	set-up cost	Nonproucti ve cost	Manufactur e cost	Material cost	Total cost
WAAM	524.48	28.29	528.49	750.28	1835.60
CNC	170.08	21.42	223.53	1718.42	2133.45

Figure 8-7 Manufacture cost comparison of WAAM and CNC machining

(case 1 part)

The figure illustrates that the total cost of WAAM is lower than CNC machining. Within the comparison items, the most major cost saving of WAAM is material cost, the manufacture cost of WAAM does not show too much superiority than CNC machining. Independent WAAM manufacture method is selected to manufacture case 1 part, therefore, the set-up cost of WAAM is higher than CNC machining.

8.2.3 Buy-to-fly ratio

Buy–to-fly ratio is an important index to evaluate the economical of manufacture method. The buy-to-fly ratio for traditional manufacture can be as high as 10:1, by means that, 90% of materials have to be removed in aerospace parts manufacture process[3]. The material wastage and time wastage in traditional manufacture is very serious as stated in literature review and WAAM provides a good choice for manufacture industry. In order to investigate the effect of buy-to-fly ratio on WAAM and CNC cost, the research work is carried on case 1 part. Assuming that the maximum size of the part keep same all the time and only change the wall thickness of part to acquire the changing of buy-to-fly ratio. WAAM and CNC cost change with buy-to-fly ratio for different material is shown in below.

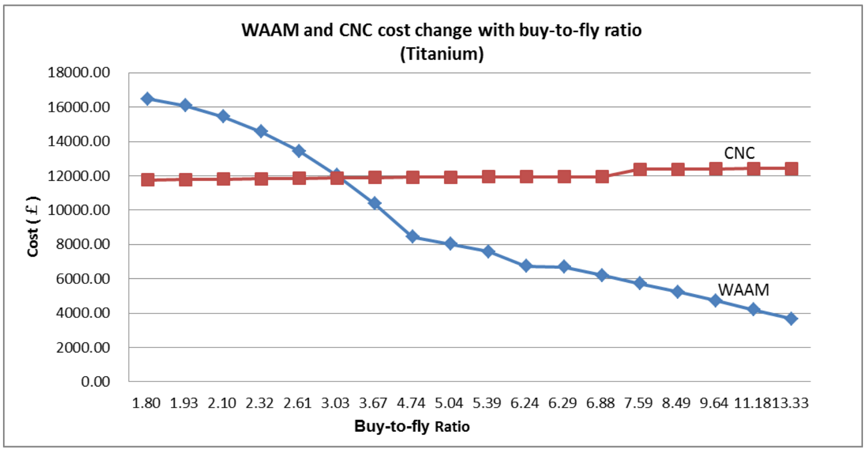


Figure 8-8 WAAM and CNC machining cost change with buy-to-fly ratio (Titanium)

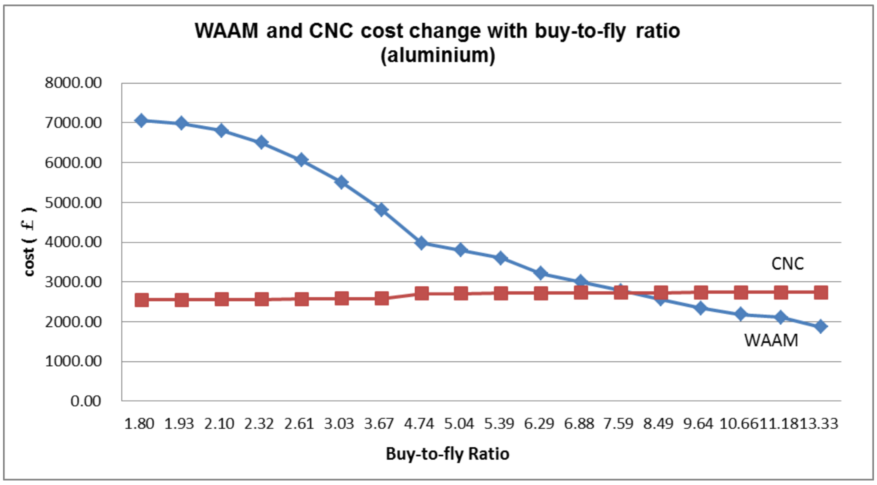


Figure 8-9 WAAM and CNC machining cost change with buy-to-fly ratio (Aluminium)

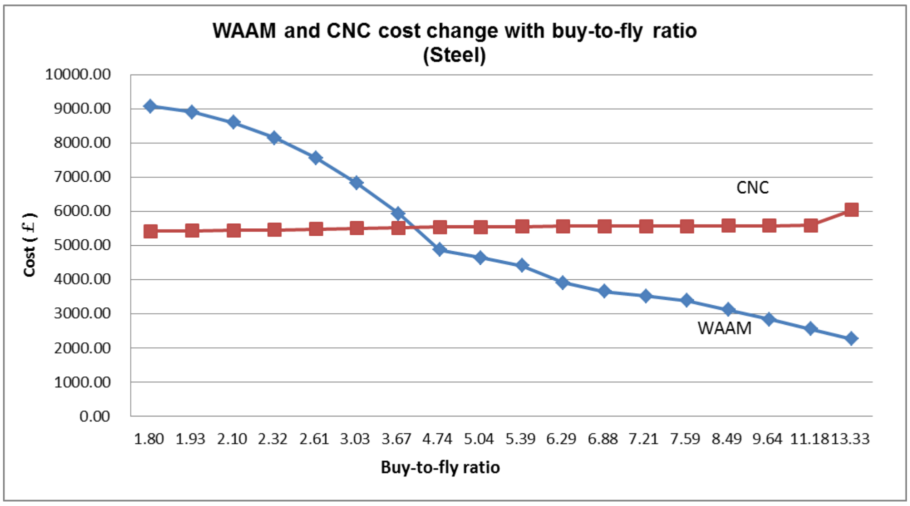


Figure 8-10 WAAM and CNC machining cost change with buy-to-fly ratio (Steel)

The result shows that with the increase of buy-to-fly ratio WAAM manufacture cost is dramatically decreased, however, CNC machining cost changes very small. With the changing of buy-to-fly ratio WAAM shows high economic in material and manufacture time reduction. Due to the material cost in CNC keep the same.

Comparing the break-even point of buy-to-fly ratio for different materials, the break- even point for titanium is nearly 3 and is 4 for steel and almost 7.5 for aluminium. Titanium shows more advantages than other materials, because the sheet metal cost of titanium is very high and reducing volume of materials can dramatically reduce the manufacture cost. Therefore, the application of WAAM in titanium is more superior to aluminium and steel.

8.2.4 Cost compare for different materials

Currently, titanium, aluminium, steel are three kinds of materials which are widely used in WAAM, The cost comparison of a part comprised by three different materials and manufactured by WAAM and CNC machining respectively are shown in **Figure 8-11** and **Figure 8-12**. WAAM choose independent method and integrated method.

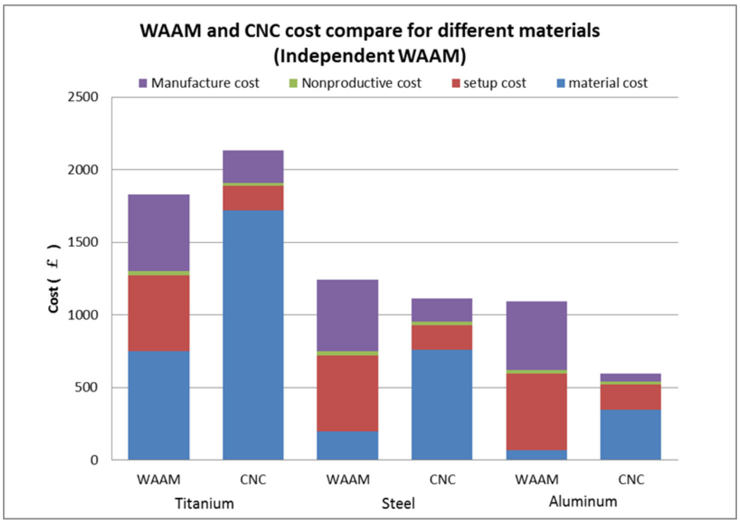


Figure 8-11 Cost comparison for different materials (Independent WAAM)

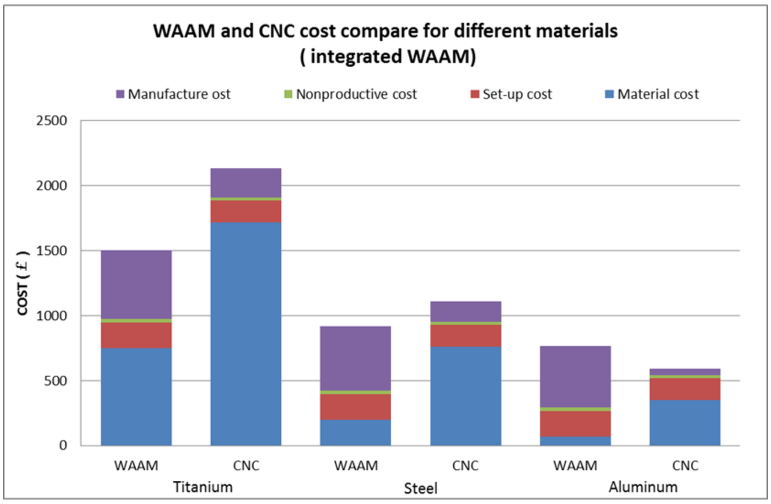


Figure 8-12 Cost comparison for different materials (integrated WAAM)

The results show that in CNC machining the major cost distributor is materials cost, however, in WAAM, the material influence is very small. Compared with CNC machining, the set-up cost is much higher than CNC machining in independent WAAM method. However, this may change with integrated WAAM method is applied. The manufacture cost for WAAM is the same for three materials because WAAM manufacture cost is determined by welding speed and welding speed is determined by wire feed speed and welding voltage and the manufacture cost is not relate to material type. But for CNC machining, the material type is relate to manufacture cost because the cutting speed is determined by the material of cutter and material of part .

8.3 Cost compare of case study 2 part

For case study 2 part, the buy-to-fly ratio is almost 14.8, the time spending comparison and cost comparison have shown in Figure 8-13 and Figure 8-14.

WAAM			CNC	
processing step	Time(hour)		Processing Step	Time(hour)
set-up time	1.5		set-up time	1.5
Non-productive	0.53		Non-productive	0.19
Deposition	5.33		Rough machining	9.05
Finish-machining	2.88		Finish-machining	2.88
Total	10.24		Total	13.62

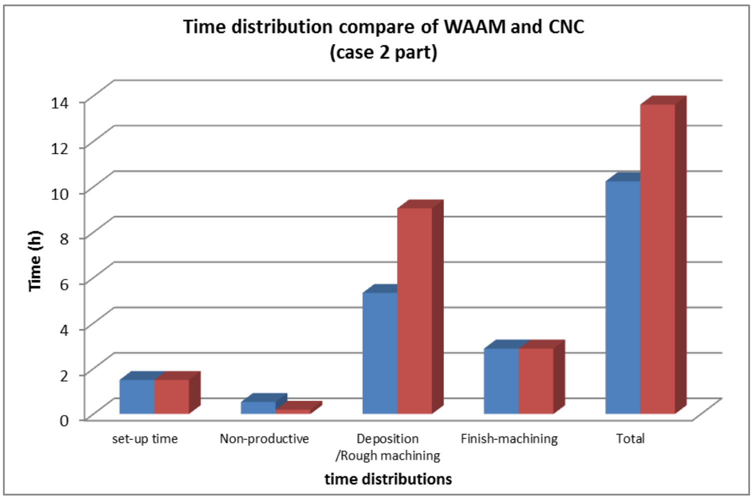


Figure 8-13 Time spending comparison for case 2 part

WAAM			CNC	
processing step	Cost(£)		Processing Step	Cost(£)
Material	1818.58		Material	11578.86
Set-up	524.48		Set-up	170.08
Nonproductive	70.08		Nonproductive	21.42
Welding	654.94		Rough-machining	1026.50
Finish-machining	326.12		Finish-machining	326.12
Total	3394.2		Total	13122.98

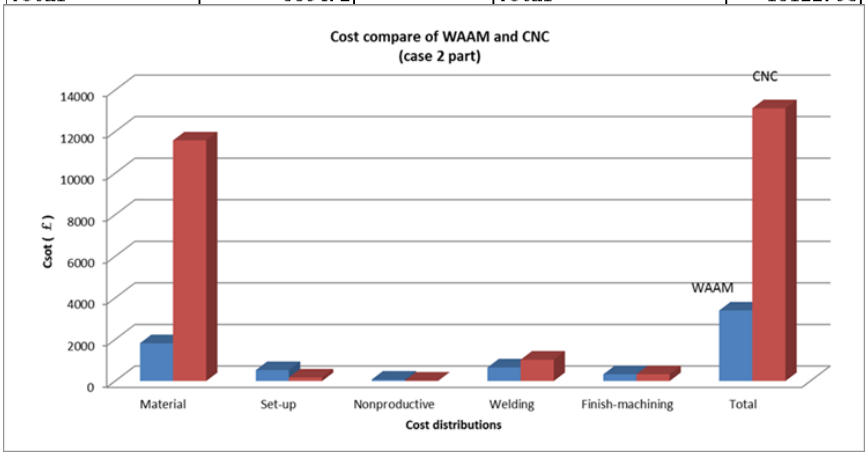


Figure 8-14 Manufacture cost comparison for case 2 part

The following interesting inferences were made from this case study:

• WAAM manufacture material cost for case 2 part took 85% less than the material cost in CNC machining and 30% less in manufacture time.

• WAAM manufacture cost for case 2 part is 75 % less than that of CNC manufacture.

Compared with CNC machining, for this part the major cost reduction of WAAM is material cost, second is the manufacture time reduction. Compared the results with case 1 part, with the increase of buy-to-fly ratio, WAAM is more economical than CNC machining in material reduction and manufacture time reduction.

9 Conclusions and Recommendations

9.1 Conclusions

This thesis considered the cost estimating process at the early stage of WAAM and CNC manufacture. The day-to-day challenges of manufacturing in a competitive environment forces company quick response to the requirements from suppliers or customers, in order to provided necessary cost information to suppliers or customers in short time. A cost model for WAAM and cost model for CNC has developed, in order to identify the cost drivers in WAAM manufacture a process planning for WAAM also developed. By combining both estimating models together, the developed spreadsheet addresses a gap in current cost estimating methods and provides a robust method for evaluating manufacture cost using WAAM and CNC. The developed models and spreadsheet has validated by the research experts in WELPC at Cranfield University. Based on two case studies proved the cost model and calculation spreadsheet is very useful when estimating a product cost in early stage.

- The largest cost contributor of WAAM is material cost. Currently wire cost per kg are much higher than billet costs, therefore a reduction in wire metal cost could reduce WAAM cost.
- Choosing integrated WAAM manufacture is more economic than independent WAAM manufacture process due to the reduced setup cost.
- Choosing partial substrate is more economic than complete substrate for WAAM manufacture where possible.
- Increased wire feed speed can dramatically reduce WAAM manufacturing cost, however, when the wire feed speed reach 6mm/min, the wire feed speed influence will tend to stabilize.
- Compared with CNC machining, for case 1 part, WAAM can reduce nearly 57% material and 14% total cost, but the WAAM manufacture time is longer than CNC machining.
- Compared with CNC machining, for case 2 part, WAAM can reduce nearly 85% material and 30% manufacture time and 75% total cost.

- The cost effectiveness of WAAM is dependent on material, for case 1 part it was found that WAAM becomes more cost effective than CNC machining for a buy-to-fly ratio > 3 for titanium, for aluminium it is >7.5 and for steel it is > 6. Therefore, WAAM is recommended for parts with high buy-to-fly ratio and Titanium shows more wide application area in WAAM than steel and aluminium.

9.2 Recommendations

The cost estimating model are not very accurate, since its only used limited information and make many assumptions in order to estimate the manufacture cost in early stage. So, the following recommendations can be suggested:

It would be interesting to carry out cooling time and waiting time investigation during WAAM manufacture process. It could be useful to accurate to estimate the manufacturing time of WAAM.

It would be very helpful to observation the practical manufacture time of WAAM and compare every cost contributions. To test the accurate the cost model and make useful improvement.

An exhaustive study of set-up and non-productive time has been made for traditional manufacture. Similar work should be carried out for WAAM. This is very useful to improve the accuracy of cost estimation.

The cost model at present is available only for three materials, in the future more materials should be added.

In this research, the cost estimation is only consider the manufacture process, however, the cost required in other aspect such as inspection and transportation also influence the manufacture cost, therefore, analysing these process cost is a feasible research topic.

In manufacture process, “learning curve” is important, it would dramatically influence the cost of manufacture, therefore, analysing the influence of “learning curve” on WAAM cost is an interesting research topic.

REFERENCES

1. Hopkinson N (2012), *Additive Manufacturing:Technology and Applications*, , British Educational Communications and Technology Agency(BECTA)(http://dera.ioe.ac.uk/id/eprint/1512), UK.

2. Karunakaran, K., Suryakumar, S., Pushpa, V., & Akula, S. (2010), "Low cost integration of additive and subtractive processes for hybrid layered manufacturing", *Robotics & Computer- integrated Manufacturing*, vol. 26, no. 5, pp. 490-499.

3. Wood, D. (2009), "Additive layer manufacturing at Airbus- reality check or view into the future", *Aerospace feature*, , no. TCT 17-3, pp. 23-24.

4. Wohlers, T. (2011), *Wohlers report, Additive manufacturing state of the industry*, Annual worldwide progress report, Wohlers associates, USA.

5. Mehnen, J., Ding, J., Lockett, H. and Kazanas, P. (2010), *Design for Wire and Arc Additive Layer Manufacturing*, CIRP Design Conference (in press).

6. Kazanas, P., Deherkar, P., Almeida, P., Lockett, H. and Williams, S. (2012), "Fabrication of geometrical features using wire and arc additive manufacture", *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 226, no. 6, pp. 1042-1051.

7. Boothroyd, G. a. K. (2006), "machined part cost estimation", in *Fundamentals of Machining and Machine Tools*, Third Edition ed, Taylor & Francis Group, , pp. 476-501.

8. *China Market Outlook for Civil Aircraft 2007-2026*, (2007), , China Aviation Industry Corporation I, Beijing, China.

9. *Global Market Forecast 2009-2029*, (2008), , COMAC, Shanghai, China.

10. Cheung, T.M., (2010), *Remaking Cinderella: the Nature and Development of China's Aviation Industry*.

11. Mark Stokes (2009), "China's Commerical Aviation Sector Looks to the future", *Project 2049 Institute*, .

12. Anonymous, (2010), "How the socio-economic benefits of rapid manufacturing can be used to off-set technological limitation", *http://www.rm-platform.com/index2.php?option=com_docman&task=doc_view&gid=626&Itemid=5*, .

13. Brandl, E., Palm, F., Michailov, V., Viehweger, B. and Leyens, C. (2011), "Mechanical properties of additive manufactured titanium (Ti–6Al–4V) blocks

deposited by a solid-state laser and wire", *Materials & Design*, vol. 32, no. 10, pp. 4665-4675.

14. Anonymous , *3D printing*, available at: http://wikipedia.org/wiki/desktop_manufacturing.

15. Song, Y., Park, S., Choi, D. and Jee, H. (2005), "3D welding and milling: Part I–a direct approach for freeform fabrication of metallic prototypes", *International Journal of Machine Tools and Manufacture*, vol. 45, no. 9, pp. 1057-1062.

16. Emille, L. (2010), *Effect of microstructure on mechanical properties of Ti-6Al-4V structures made by Additive Layer Manufacturing* (MSc thesis), Cranfield University, .

17. Baufeld, B., Biest, O. V. d. and Gault, R. (2010), "Additive manufacturing of Ti–6Al–4V components by shaped metal deposition: Microstructure and mechanical properties", *Materials & Design*, vol. 31, Supplement 1, no. 0, pp. S106-S111.

18. Scallan, P. (2003), *process planning – the design/manufacture interface*, Butterworth Heinemann.

19. Ben-Arieh, D. and Qian, L. (2003), "Activity-based cost management for design and development stage", *International Journal of Production Economics*, vol. 83, no. 2, pp. 169-183.

20. Shehab, E. M. and Abdalla, H. S. (2001), "Manufacturing cost modelling for concurrent product development", *Robotics and Computer-Integrated Manufacturing*, vol. 17, no. 4, pp. 341-353.

21. Malstron, E. M. (ed.) (1984), *Manufacturing Cost Engineering manufacturing Handbook*, Marcel Dekker, New York.

22. William, W. (ed.) (1989), *Realisric cost estimation for manufacturing*, 2nd Ed. ed, Society of Manufacyuting Engineers, Publications development Dept. UK.

23. Niazi, A., Dai, J., Seneviratne, L. and Balabani, S. (2006), "Product Cost Estimation: Technique Classification and Methodology Review", *Journal of Manufacturing Science and Engineering*, vol. 128, pp. 563-575.

24. Jung, J. (2002), "Manufacturing cost estimation for machined parts based on manufacturing features", *Journal of Intelligent Manufacturing*, vol. 13, no. 4, pp. 227-238.

25. Qian, L. and Ben-Arieh, D. (2008), "Parametric cost estimation based on activity-based costing: A case study for design and development of rotational parts", *International Journal of Production Economics*, vol. 113, no. 2, pp. 805-818.

26. T, L.,. and C, O. (1997), "Developing an integrated framework for feature-based early manufacturing cost esitmation", *the Internatonal Journal of Advanced Mnaufacturing Technology,* vol. 13(9), pp. 618-629.

27. Hopkinson, N. and Dicknes, P. (2003), "Analysis of rapid manufacturing—using layer manufacturing processes for production", *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science,* vol. 217, no. 1, pp. 31-39.

28. Ruffo, M., Tuck, C. and Hague, R. (2006), "Cost estimation for rapid manufacturing - laser sintering production for low to medium volumes", *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* vol. 220, no. 9, pp. 1417-1427.

29. Ruffo, M., Tuck, C. and Hague, R. (2006), "Empirical laser sintering time estimator for Duraform PA", *International Journal of Production Research,* vol. 44, no. 23, pp. 5131-5146.

30. Bhoopala.Shettigar, K. (2010), *Feature based model for RUAM cost modeling and comparative cost analysis* Cranfield University, .

31. *Machinery's Handbook,* (1973), 19th ed. ed, Industrial Press, Inc., New York.

32. JiaNing, G. (2012), *Feature based cost and carbon emission modelling for wire and arc additive manufacturing* (unpublished MSc(forthcoming) thesis), Cranfield University, .

33. Ding, J., Colegrove, P., Mehnen, J., Ganguly, S., Sequeira Almeida, P. M., Wang, F. and Williams, S. (2011), "Thermo-mechanical analysis of Wire and Arc Additive Layer Manufacturing process on large multi-layer parts", *Computational Material Science*, , no. 50, pp. 3315-3322.

34. Sequeira Alemeida, P. M. (2012), *Process control and development in wire and arc additive manufacturing* (unpublished PhD thesis thesis), School of Applied Science(SAS), Welding Engineering and Laser Processing Centre(WELPC), .

35. Song, Y., Park, S. and Chae, S. (2005), "3D welding and milling: part II—optimization of the 3D welding process using an experimental design approach", *International Journal of Machine Tools and Manufacture,* vol. 45, no. 9, pp. 1063-1069.

36. John, N. (1992), *Advanced welding processes,* IOP Publishing Ltd, Bristo, UK.

37. Mattias, L. (2009), *Additive-layer-manufacturing by CMT using Cu97Si3 wire on steel* .

APPENDICES

Appendix A The details of cost estimation spreadsheet

A.1 The scope of cost estimation spreadsheet

	A	B	C	D	E	F	G
1	WAAM and CNC Machining Cost Estimation and Comparison						
2	Product Information input		unit				
3	Volume of Part	1408000	mm^3		Spreadsheet Instructions		Input Data
4	Surface Area of Part	292000	mm^2				Select Option from List
5	Batch Size	1				Reset	Default Value
6	WAAM Manufacture Cost Estimation		Reset		CNC Manufacture Cost Estimation		
7	Manufacture Method	Independent WAAM			Manufacture Method	CNC	UNIT
8	Material Data				Material Data		
9	Material Type	Titanium			Material Type	Titanium	
10	Wire Diameter	1.2	mm		Density	4428.00	kg/m^3
11	Material Density	4428.00	kg/m^3		Thickness	Thickness<12.7mm	mm
12	Wire Metal Cost	150	£/kg		Sheet Metal Cost	60.00	£/kg
13	Substrate Thickness	Thickness<12.7mm	mm		Equipment Data		
14	Substrate Metal Cost	60.00	£/kg		Machine Cost	64260	£
15	WAAM Data				Machine hourly Rate	13.39	£/hr
16	Machine Cost	92000	£		Operator hourly Rate	100	£/hr
17	Machine hourly Rate	20.18	£/hr		Set-up Time	1.5	h
18	Operator hourly Rate	100	£/hr		Non-productive Time	85	s
19	Consumable cost	2.7	£/hr		Available Power	5.215	kw
20	Set-up Time	1.5	h		Cutter Data		
21	Non-productive Time	0.19	h		Cutter Material	Brazed Carbide	
22	Finish-machining Data				Taylor Tool-life Index	0.25	
23	Equipment	CNC			Cutting Speed	79	m/min
24	Cutter Material	Brazed Carbide			Feed per Tooth	0.15	mm
25	Taylor Tool-life Index	0.25			Surface Generation Rate	0.012	m^2/min
26	Cutting speed	79	m/min		Specific Cutting Energy	0.05	$kw/cm^3/min$
27	Feed per Tooth	0.15	mm		Input		
28	Surface Generation Rate	0.012	m^2/min		Volume of Billet	6468000	mm^3
29	Machine Cost	64260	£		Number of Operations	8	Times
30	Machine hour Rate	13.39	£/h		Calculation process		
31	Operator hour Rate	100	£/h		Buy-to-Fly Ratio	4.59	
32	Set-up Time	1.5	h		Time for Rough Machining(Volume)	0.81	h
33	Non-productive Time	85	s		Time for Rough Machining(Surface)	0.41	h
34	Input				Time for Finish Machining(Surface)	0.46	h
35	Volume of Deposition	608000	mm^3		Corrected Rough Machining Time (including tool replacement cost)	1.36	h
36	Volume of Substrate	924000	mm^3		Corrected Finish-machining Time (including tool replacement cost)	0.62	h
37	Part Build Efficiency	0.80	%		Results		
38	Wire Feed Speed	3.00	m/min		Time for Manufacture	1.97	h
39	Number of Deposition Operations	1	Times		Material Cost	1718.42	£
40	Number of Finish-machining Operations	2	Times		Set-up Cost	170.08	£
41	Build Time Efficiency	0.95	%		Non-productive Cost	21.42	£
42	Calculation Process				Manufacture Cost	223.53	£
43	Deposition Rate	0.90	kg/h		Total CNC Cost	2133.45	£
44	Time for Deposition	3.73	h				
45	Time for Finish-machining	0.46	h				
46	Corrected Finish-machining Time (including tool replacement cost)	0.62	h				
47	Substrate Material Cost	245.49	£				
48	Welding Material Cost	20.52	£				
49	Results						
50	Time for Manufacture	4.05	h				
51	Material Cost	70.42	£				
52	Set -up Cost	184.31	£				
53	Non-productive Cost	28.29	£				
54	Welding Cost	458.73	£				
55	Finish-machining Cost	13.55	£				
56	Total Manufacturing Cost	472.28	£				
57	Shielding Gas Cost	0.0555	£				
58	Wire Change Cost	2.40	£				
59	Total WAAM Cost	757.76	£				

A.2 The sources data of cost estimation spreadsheet

Source Data

WAAM

WAAM material Data

Material	Density (kg/m^3)	Wire Metal cost (£/kg)	
Titanium	4428	150.00	Expert suggest
Steel	7850	15.00	
Aluminum	2700	10.00	

WAAM Equipment Data

WAAM Shielding Gas Data

	Gas flow rate (mm3/min)	Cost per cylinder (£)	Volume of cylinder (m3)	Shielding gas cost per hour	Shielding gas cost	
Aluminum	16000	154.98	10	0.01487808	0.137123761	expert suggest
Steel	15000	154.98	10	0.0139482	0.128553526	
Titanium	37000	154.98	10	0.03440556	0.317098697	

WAAM wire change Data

Mass of wire per roll (kg)	Wire change time (s)	wire change cost	
7	300	5.63	Expert suggest

WAAM and CNC

	Machine Cost	Operator houre rate	Set-up time (h)	Nonproductive time	
WAAM	92,000	100.00	1.50	83.00	Expert suggested and Boothroyd's
CNC	64,260	100	1.50	85.00	

CNC

CNC material Data

Material	Density (kg/m3)	sheet <12.7mm £/kg	sheet >12.7mm £/kg	
Aluminum	2700	20.00	25.00	Validation
Steel	7850	15.00	20.00	
Titanium	4428	60.00	65.00	

CNC machine cost

Part Weight	0-25kg	25-45kg	45-250kg	>250kg	
Machine cost	64260.00	213570.00	420210.00	568890.00	Boothroyd's book
2011	102000.00	339000.00	667000.00	903000.00	
2006	90000.00	300000.00	600000.00	800000.00	

CNC Machine Available Power(KW)

Part Weight	0-25(kg)	25-45(kg)	45-450(kg)	>450(kg)	
Available Power	5.22	14.9	29.80	44.7	Machinery Data Handbook

Cutter data for CNC

Cutter material	Taylor tool life index	
HSS	0.125	Boothroyd's book
Brazed Carbide	0.25	

CNC Manufacture parameters

Material	Specific Cutting Energy (HSS tool) (kw/cm3/min)	Specific Cutting Energy (Brazed Carbide tool)	
Aluminum	0.015	0.015	Machinery Data Handbook
Steel	specific Cutting Energy (HSS tool)	0.050	
Titanium	0.050	0.050	

Material	cutting speed(HSS) m/min	feed per tooth(HSS) mm/min	cutting speed (Brazed Carbide tool) m/min	feed per tooth (Brazed Carbide tool)	Machinery data handbook Cutting type: end milling Depth of cutter: 1.5mm Cutter diameter: 18mm
Aluminum	185.00	0.20	305	0.20	
Steel	27.00	0.102	155	0.15	
Titanium	27.00	0.13	79	0.15	

A.3 WAAM cost estimation spreadsheet expansion

	A	B	C
6		WAAM Manufacture Cost Estimation	Reset
7	Manufacture Method	Independent WAAM	
8	Material Data		
9	Material Type	Aluminum	
10	Wire Diameter	1.2	mm
11	Material Density	=VLOOKUP(B9,'source data'!A5:B7,2,FALSE)	kg/m^3
12	Wire Metal Cost	=VLOOKUP(B9,'source data'!A5:C7,3,FALSE)	£ /kg
13	Substrate Thickness	Thickness<12.7mm	mm
14	Substrate Metal Cost	=IF(B13="Thickness<12.7mm",VLOOKUP(B9,'source data'!A29:C31,3,FALSE),IF(B13="Thickness>12.7mm",VLOOKUP(E	£ /kg
15	WAAM Data		
16	Machine Cost	92000	£
17	Machine hourly Rate	=B16/(8*5*40*5)/57%	£ /hr
18	Operator hourly Rate	100	£ /hr
19	Consumable cost	2.7	£ /hr
20	Set-up Time	1.5	h
21	Non-productive Time	=(1-B41)*B44	h
22	Finish-machining Data		
23	Equipment	CNC	
24	Cutter Material	Brazed Carbide	
25	Taylor Tool-life Index	=VLOOKUP(B24,'source data'!A45:B46,2,FALSE)	
26	Cutting speed	=IF(B24="Brazed Carbide",VLOOKUP(B9,'source data'!A55:D57,4,FALSE),IF(B24="HSS",VLOOKUP(B9,'source data'!A5	m/min
27	Feed per Tooth	=IF(B24="Brazed Carbide",VLOOKUP(B9,'source data'!A55:E57,5,FALSE),IF(B24="HSS",VLOOKUP(B9,'source data'!A5	mm
28	Surface Generation Rate	=B26*B27/1000	m^2/min
29	Machine Cost	64260	£
30	Machine hour Rate	=B29/(8*5*40*5)/60%	£ /h
31	Operator hour Rate	100	£ /h
32	Set-up Time	1.5	h
33	Non-productive Time	85	s
34	Input		
35	Volume of Deposition	608000	mm^3
36	Volume of Substrate	924000	mm^3
37	Part Build Efficiency	0.8	%
38	Wire Feed Speed	3	m/min
39	Number of Deposition Operations	1	Times
40	Number of Finish-machining Operations	2	Times
41	Build Time Efficiency	0.95	%
42	Calculation Process		
43	Deposition Rate	=6/4*PI()*B10^2*B38*B11*10^-5	kg/h
44	Time for Deposition	=B35*B11/B37*10^-9/B43	h
45	Time for Finish-machining	=60*B4/(B28*0.89)*10^-6/3600	h
	Corrected Finish-machining Time		h

46	Corrected Finish-machining Time (including tool replacement cost)	=B45*(1/(1-B25))	h
47	Substrate Material Cost	=B36*B11*B14*10^-9	£
48	Welding Material Cost	=B35/B37*B11*B12*10^-9	£
49	Results		
50	Time for Manufacture	=B44/B41+B46	h
51	Material Cost	=(B47+B48)	£
52	Set -up Cost	=IF(B7="Independent WAAM",B20/B5*(B17+B18+B19)+B32/B5*(B30+B31)*B40,B20/B5*(B17+B18+B19))	£
53	Non-productive Cost	=(B21*(B17+B18+B19)*B39+B33/3600*(B30+B31)*B40)	£
54	Welding Cost	=(B44*(B17+B18+B19))	£
55	Finish-machining Cost	=(B46*(B30+B31))	£
56	Total Manufacturing Cost	=B54+B55	£
57	Shielding Gas Cost	=(VLOOKUP(B9,'source data'!A12:F14,6,FALSE))	£
58	Wire Change Cost	=('source data'!C18)	£
59	Total WAAM Cost	=B51+B52+B53+B54+B55+B57+B58	£

A.4 CNC cost estimation spreadsheet expansion

	D	E	F	G
6			CNC Manufacture Cost Estimation	
7		Manufacture Method	CNC	UNIT
8		Material Data		
9		Material Type	=B9	
10		Density	=VLOOKUP(F9,'source data'!A5:B7,2,FALSE)	kg/m³
11		Thickness	Thickness<12.7mm	mm
12		Sheet Metal Cost	=IF(F11="Thickness<12.7mm",VLOOKUP(F9,'source data'!A29:C31,3,FALSE),IF(F11="Thickness>12.7mm",VLOOKUP(F9,'sc	£ /kg
13		Equipment Data		
14		Machine Cost	64260	£
15		Machine hourly Rate	=F14/(5*8*40*5)/60%	£ /hr
16		Operator hourly Rate	100	£ /hr
17		Set-up Time	1.5	h
18		Non-productive Time	85	s
19		Available Power	=IF(B3*F10*10^-9<25,VLOOKUP(E19,'source data'!A41:B41,2,FALSE),IF(B3*F10*10^-9>25,VLOOKUP(E19,'source data'!A4	kw
20		Cutter Data		
21		Cutter Material	Brazed Carbide	
22		Taylor Tool-life Index	=VLOOKUP(F21,'source data'!A45:B46,2,FALSE)	
23		Cutting Speed	=IF(F21="Brazed Carbide",VLOOKUP(F9,'source data'!A55:D57,4,FALSE),IF(F21="HSS",VLOOKUP(F9,'source data'!A55:D5	m/min
24		Feed per Tooth	=IF(F21="Brazed Carbide",VLOOKUP(F9,'source data'!A55:E57,5,FALSE),IF(F21="HSS",VLOOKUP(F9,'source data'!A55:C5	mm
25		Surface Generation Rate	=F23*F24/1000	m²/min
26		Specific Cutting Energy	=IF(F21="Brazed Carbide",VLOOKUP(F9,'source data'!A50:C52,3,FALSE),IF(F21="HSS",VLOOKUP(F9,'source data'!A50:B5	kw/cm³/min
27		Input		
28		Volume of Billet	6468000	mm³
29		Number of Operations	8	Times
30		Calculation process		
31		Buy-to-Fly Ratio	=F28/B3	
32		Time for Rough Machining(Volume)	=60*(F28-B3)*F26/F19*10^-3/3600	h
33		Time for Rough Machining(Surface)	=60*B4/F25*10^-6/3600	h
34		Time for Finish Machining(Surface)	=60*B4/(F25*0.89)*10^-6/3600	h
35		Corrected Rough Machining Time (including tool replacement cost)	=F32*(1+(F22/(1-F22)*(F33/F32)*(1/F22)))	h
36		Corrected Finish-machining Time (including tool replacement cost)	=F34*(1/(1-F22))	h
37		Results		
38		Time for Manufacture	=(F35+F36)	h
39		Material Cost	=(F28*F10*F12*10^-9)	£
40		Set-up Cost	=F17/B5*(F15+F16)	£
41		Non-productive Cost	=(F18*F29/3600*(F15+F16))	£
42		Manufacture Cost	=(F38*(F15+F16))	£
43		Total CNC Cost	=F39+F40+F41+F42	£

Appendix B Calculation data

B.1 Buy-to-fly data

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	Number	Length	Width	Height	Stiffener Thickness	Plate Thickness	Box1 Length	Box3 Length	Voulme of part	Surface of part	Weight of part	Volume of Billet	Volume of deposition	Volume of substrate	Surface rough	Surface finish	Buy-to-fly Ratio	Batch size
2	Titanium																	
3	1(complete substrate	400	200	50	10	10	125	125	1408000	292000	6.29	6468000	1408000	924000	411200	136800	4.59	1
4	2(partial substrate)	400	200	50	10	10	125	125	1408000	292000	6.29	6468000	608000	924000	411200	136800	4.59	1
5	1(buy-to-fly ratio)	800	400	100	50	50	125	100	23000000	1030000	102.76	41328000	7000000	17220000	1316400	330000	1.80	1
6	2	800	400	100	45	45	125	100	21429000	1050500	95.74	41328000	7029000	15498000	1349100	362700	1.93	1
7	3	800	400	100	40	40	125	100	19712000	1072000	88.07	41328000	6912000	13776000	1383200	396800	2.10	1
8	4	800	400	100	35	35	125	100	17843000	1094500	79.72	41328000	6643000	12054000	1418700	432300	2.32	1
9	5	800	400	100	30	30	125	100	15816000	1118000	70.67	41328000	6216000	10332000	1455600	469200	2.61	1
10	6	800	400	100	25	25	125	100	13625000	1142500	60.88	41328000	5625000	8610000	1493900	507500	3.03	1
11	7	800	400	100	20	20	125	100	11264000	1168000	50.33	41328000	4864000	6888000	1533600	547200	3.67	1
12	8	800	400	100	15	15	125	100	8727000	1194500	38.99	41328000	3927000	5166000	1574700	588300	4.74	1
13	9	800	400	100	14	14	125	100	8197952	1199920	36.63	41328000	3717952	4821600	1583088	596688	5.04	1
14	10	800	400	100	13	13	125	100	7661576	1205380	34.23	41328000	3501576	4477200	1591532	605132	5.39	1
15	11	800	400	100	11.1	11.1	125	100	6622101	1215864	29.59	41328000	3070101	3822840	1607730	621330	6.24	1
16	12	800	400	100	11	11	125	100	6566648	1216420	29.34	41328000	3046648	3788400	1608588	622188	6.29	1
17	13	800	400	100	10	10	125	100	6008000	1222000	26.84	41328000	2808000	3444000	1617200	630800	6.88	1
18	14	800	400	100	9	9	125	100	5441832	1227620	24.31	41328000	2561832	3099600	1625868	639468	7.59	1
19	15	800	400	100	8	8	125	100	4868096	1233280	21.75	41328000	2308096	2755200	1634592	648192	8.49	1
20	16	800	400	100	7	7	125	100	4286744	1238980	19.15	41328000	2046744	2410800	1643372	656972	9.64	1
21	17	800	400	100	6	6	125	100	3697728	1244720	16.52	41328000	1777728	2066400	1652208	665808	11.18	1
22	18(buy-to-fly ratio)	800	400	100	5	5	125	100	3101000	1250500	13.86	41328000	1501000	1722000	1661100	674700	13.33	1

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	Number	Length	Width	Height	Stiffener Thickness	Plate Thickness	Box1 Length	Box3 Length	Voulme of part	Surface of part	Weight of part	Volume of Billet	Volume of deposition	Volume of substrate	Surface rough	Surface finish	Buy-to-fly Ratio	Batch size
2	Aluminium																	
3	(totally substrate 1	400	200	50	10	10	125	125	1408000	292000	6.29	6468000	1408000	924000	411200	136800	4.59	1
4	(partly substrate) 2	400	200	50	10	10	125	125	1408000	292000	6.29	6468000	608000	924000	411200	136800	4.59	1
5	(buy-to-fly ratio) 1	800	400	100	50	50	125	100	23000000	1030000	62.10	41328000	7000000	17220000	1316400	330000	1.80	1
6	2	800	400	100	45	45	125	100	21429000	1050500	57.86	41328000	7029000	15498000	1349100	362700	1.93	1
7	3	800	400	100	40	40	125	100	19712000	1072000	53.22	41328000	6912000	13776000	1383200	396800	2.10	1
8	4	800	400	100	35	35	125	100	17843000	1094500	48.18	41328000	6643000	12054000	1418700	432300	2.32	1
9	5	800	400	100	30	30	125	100	15816000	1118000	42.70	41328000	6216000	10332000	1455600	469200	2.61	1
10	6	800	400	100	25	25	125	100	13625000	1142500	36.79	41328000	5625000	8610000	1493900	507500	3.03	1
11	7	800	400	100	20	20	125	100	11264000	1168000	30.41	41328000	4864000	6888000	1533600	547200	3.67	1
12	8	800	400	100	15	15	125	100	8727000	1194500	23.56	41328000	3927000	5166000	1574700	588300	4.74	1
13	9	800	400	100	14	14	125	100	8197952	1199920	22.13	41328000	3717952	4821600	1583088	596688	5.04	1
14	10	800	400	100	13	13	125	100	7661576	1205380	20.69	41328000	3501576	4477200	1591532	605132	5.39	1
15	11	800	400	100	11	11	125	100	6566648	1216420	17.73	41328000	3046648	3788400	1608588	622188	6.29	1
16	12	800	400	100	10	10	125	100	6008000	1222000	16.22	41328000	2808000	3444000	1617200	630800	6.88	1
17	13	800	400	100	9	9	125	100	5441832	1227620	14.69	41328000	2561832	3099600	1625868	639468	7.59	1
18	14	800	400	100	8	8	125	100	4868096	1233280	13.14	41328000	2308096	2755200	1634592	648192	8.49	1
19	15	800	400	100	7	7	125	100	4286744	1238980	11.57	41328000	2046744	2410800	1643372	656972	9.64	1
20	15	800	400	100	6.3	6.3	125	100	3875240	1242994	10.46	41328000	1859240	2169720	1649551	663151	10.66	1
21	17	800	400	100	6	6	125	100	3697728	1244720	9.98	41328000	1777728	2066400	1652208	665808	11.18	1
22	(buy-to-fly ratio) 1	800	400	100	5	5	125	100	3101000	1250500	8.37	41328000	1501000	1722000	1661100	674700	13.33	1

	Number	Length	Width	Height	Stiffener Thickness	Plate Thickness	Box1 Length	Box3 Length	Voulme of part	Surface of part	Weight of part	Volume of Billet	Volume of deposition	Volume of substrate	Surface rough	Surface finish	Buy-to-fly Ratio	Batch size
2	Steel																	
3	1(totally substrate	400	200	50	10	10	125	125	1408000	292000	6.29	6468000	1408000	924000	411200	136800	4.59	1
4	2(partly substrate)	400	200	50	10	10	125	125	1408000	292000	6.29	6468000	608000	924000	411200	136800	4.59	1
5	(buy-to-fly ratio) 1	800	400	100	50	50	125	100	23000000	1030000	180.55	41328000	7000000	17220000	1316400	330000	1.80	1
6	2	800	400	100	45	45	125	100	21429000	1050500	168.22	41328000	7029000	15498000	1349100	362700	1.93	1
7	3	800	400	100	40	40	125	100	19712000	1072000	154.74	41328000	6912000	13776000	1383200	396800	2.10	1
8	4	800	400	100	35	35	125	100	17843000	1094500	140.07	41328000	6643000	12054000	1418700	432300	2.32	1
9	5	800	400	100	30	30	125	100	15816000	1118000	124.16	41328000	6216000	10332000	1455600	469200	2.61	1
10	6	800	400	100	25	25	125	100	13625000	1142500	106.96	41328000	5625000	8610000	1493900	507500	3.03	1
11	7	800	400	100	20	20	125	100	11264000	1168000	88.42	41328000	4864000	6888000	1533600	547200	3.67	1
12	8	800	400	100	15	15	125	100	8727000	1194500	68.51	41328000	3927000	5166000	1574700	588300	4.74	1
13	9	800	400	100	14	14	125	100	8197952	1199920	64.35	41328000	3717952	4821600	1583088	596688	5.04	1
14	10	800	400	100	13	13	125	100	7661576	1205380	60.14	41328000	3501576	4477200	1591532	605132	5.39	1
15	11	800	400	100	11	11	125	100	6566648	1216420	51.55	41328000	3046648	3788400	1608588	622188	6.29	1
16	12	800	400	100	10	10	125	100	6008000	1222000	47.16	41328000	2808000	3444000	1617200	630800	6.88	1
17	13	800	400	100	10	10	125	100	5731520	1224749	44.99	41328000	2688320	3275244	1621440	635040	7.21	1
18	14	800	400	100	9	9	125	100	5441832	1227620	42.72	41328000	2561832	3099600	1625868	639468	7.59	1
19	15	800	400	100	8	8	125	100	4868096	1233280	38.21	41328000	2308096	2755200	1634592	648192	8.49	1
20	16	800	400	100	7	7	125	100	4286744	1238980	33.65	41328000	2046744	2410800	1643372	656972	9.64	1
21	17	800	400	100	6	6	125	100	3697728	1244720	29.03	41328000	1777728	2066400	1652208	665808	11.18	1
22	(buy-to-fly ratio)18	800	400	100	5	5	125	100	3101000	1250500	24.34	41328000	1501000	1722000	1661100	674700	13.33	1

B.2 Batch size data

Number	Length	Width	Heigh	Stiffener Thickness	Plate Thickness	Box1 Length	Box3 Length	Voulme of part	Surface of part	Weight of part	Volume of Billet	Volume of deposition	Volume of substrate	Surface rough	Surface finish	Buy-to-fly Ratio	Batch size
Batch Size																	
1	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	1
2	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	2
3	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	3
4	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	4
5	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	5
6	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	6
7	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	7
8	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	8
9	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	9
10	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	10
11	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	15
12	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	20
13	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	25
14	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	30
15	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	35
16	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	40
17	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	45
18	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	50
19	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	55
20	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	60
21	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	65
22	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	70
23	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	75
24	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	80
25	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	85
26	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	90
27	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	95
28	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	500
29	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	1000
30	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	1500
31	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	2000
32	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	2500
33	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	3000
34	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	3500
35	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	4000
36	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	5000

B.3 Wire feed speed data

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	Number	Length	Width	Height	Stiffener Thickness	Plate Thickness	Box1 Length	Box3 Length	Voulme of part	Surface of part	Weight of part	Volume of Billet	Volume of deposition	Volume of substrate	Surface rough	Surface finish	Buy-to-fly Ratio	wire feed speed
2	wire feed speed	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18.0
3	1	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	0. 5
4	2	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	1. 0
5	3	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	1. 5
6	4	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	2. 0
7	5	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	2. 5
8	6	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	3. 0
9	7	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	3. 5
10	8	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	4. 0
11	9	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	4. 5
12	10	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	5. 0
13	11	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	5. 5
14	12	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	6. 0
15	13	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	6. 5
16	14	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	7. 0
17	15	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	7. 5
18	11	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	8. 0
19	12	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	8. 5
20	13	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	9. 0
21	14	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	9. 5
22	15	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	10. 0
23	12	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	10. 5
24	13	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	11. 0
25	14	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	11. 5
26	15	800	400	100	11	11	125	100	6566648	1216420	17. 73	41328000	3046648	3788400	1608588	622188	6. 29	12. 0